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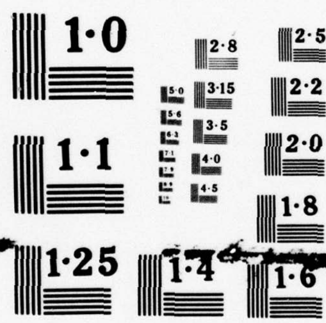
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A PRELIMINARY INVESTIGATION OF THE PRODUCTION OF STABLE FOGS UNDER SUBSATURATED CONDITIONS

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by

E.J. Mack, R.J. Anderson and J.T. Hanley

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Section 1

INTRODUCTION AND SUMMARY

Under Contract No. N00019-78-C-0349 from the Naval Air Systems Command, Calspan Corporation initiated an experimental investigation of the feasibility of producing stable fogs under conditions of subsaturated relative humidity. The objectives of this limited laboratory investigation were; (1) to determine the efficiency of pyrotechnically-generated, hygroscopic aerosols in producing conditions of restricted visibility (at both visible and infrared wavelengths) at relative humidities $<$ 100%; and (2) to assess the utility of evaporation retardants in increasing the persistence (lifetime) of the artificial fogs with lowering relative humidity. In the experiments, measurements of aerosol size spectra (0.01 micron µm - 10 ~~µm~~ * diameter) and optical extinction at both visible and infrared wavelengths were obtained as functions of time and changing relative humidity for a variety of aerosol concentration levels. p. 2

The laboratory investigation was carried out in Calspan's 590 M^3 Chamber. The facility's large size (9 m diameter by 9 m high) minimized wall effects, provided relatively long path lengths for extinction measurements, and provided for a useful aerosol lifetime of many hours. A complete air handling capability permitted the removal of virtually all particulate and gaseous contaminants prior to each experiment, the introduction of specified aerosols, and control of humidity from 20 to 98% RH. Calspan's chamber facility and instrumentation pertinent to this investigation are described in Section 2.

The scope of this initial effort was limited to an experimental evaluation of the efficiency of "Salty Dog" pyrotechnic aerosols in producing conditions of restricted visibility at subsaturated humidities and the influence of an evaporation retardant, cetyl alcohol, in prolonging the lifetime of such artificial fogs at lower relative humidities. In previous experiments conducted at this laboratory, cetyl alcohol vapors applied to aqueous fog aerosols (i.e., droplets of 4-30 µm diameter) were found to be effective in retarding complete dissipation of "natural" fog (Kocmond et al., 1972). In the current

* microns

experiments, hazes/fogs were generated within the chamber by burning a prescribed quantity of the pyrotechnic material under prescribed humidity conditions. After the cloud had stabilized, its characteristics were measured; relative humidity in the chamber was then lowered, and the response of the fog was monitored. In companion experiments, cetyl alcohol vapors were mixed with the pyrotechnic aerosols immediately upon generation in a "mixing chamber" prior to being vented into the chamber; again the treated fog was monitored as relative humidity was lowered.

In all, 19 primary experiments, including three "natural" fogs, were conducted. The Salty Dog pyrotechnics, when burned, produced copious quantities of aerosols ($\sim 10^{13}$/gram >0.01 μm diameter and $\sim 10^{10}$/gram >1.0 μm diameter); relatively few particles >5 μm diameter were observed. At airborne concentrations of $\sim 10^4$ cm^{-3} and 10^1 cm^{-3} for particles of >0.01 and >1.0 μm diameter, respectively, visibility restrictions (visible wavelengths) of ∼10 km were observed at relative humidities < 85%. At particle concentrations of 10^5 and 10^3 cm^{-3} (for >0.01 and >1.0 μm diameter aerosols, respectively) and relative humidities of 95-97%, visibility restrictions of ∼25 m were achieved. The Salty Dog aerosol fogs were found to be extremely stable, with visibility improvements of only a factor of 2 occuring when relative humidity was reduced 10%.* Cetyl alcohol was found to be ineffective in reducing the visibility improvement factor. Results of the experiments are presented and discussed in greater detail in Section 3. Visibility and aerosol data from each experiment are provided in Appendix A.

A brief outline of the principal conclusions derived from this investigation and our recommendations to NASC are provided in Section 5.

* The evaporation retardant,

Section 2
EXPERIMENTAL FACILITIES AND PROCEDURES

2.1 Facilities and Instrumentation

The Calspan chamber is a cylinder, 9.14 meters (30 feet) in diameter and 9.14 meters high, enclosing a volume of 590 m^3 (20,800 ft^3). A cut-away view of the entire facility is illustrated in Figure 1. The 1.25 cm thick steel wall of the chamber is designed to withstand pressure differentials of 60 kilopascals (6.1 m of water); however, the Pyrex cover plates of an irradiation system currently limit pressure differentials to about 3.9 kilopascals (40 cm of water). The inner chamber surface is coated with a fluoroepoxy type urethane (developed at the Naval Research Laboratory, Washington, D. C.) which has surface energy and reactivity properties comparable to those of the FEP Teflon. Illumination (for photochemical experiments) within the chamber is provided by 28.6 kw of fluorescent blacklight and sun lamps installed inside 24 lighting modules and arranged in eight vertical channels attached to the wall of the chamber. A photograph of the interior of the chamber is presented in Figure 2.

Air purification for the chamber is accomplished by recirculating the air through a series of absolute and activated carbon filters. Nearly all gaseous contaminants and particulate matter can be removed from the chamber air in several hours of filtration. Typically, aerosol concentration is halved every 10 minutes. Filtered air generally contains no measurable Aitken particles, less than 0.1 ppm NO_x, 0.2 ppmC non-methane HC, and no measurable SO_2 or ozone.

The chamber is equipped with washdown, humidification, and dehumidification systems. The recirculating washdown system consists of a stainless steel spray head which rotates on two axes and can wet all of the chamber surfaces with distilled water or cleaning solution. Generally, the procedure is to first wash the chamber surfaces with a 5% solution of a laboratory glass cleaning agent followed by two or three rinsings with tap water and two final rinsings

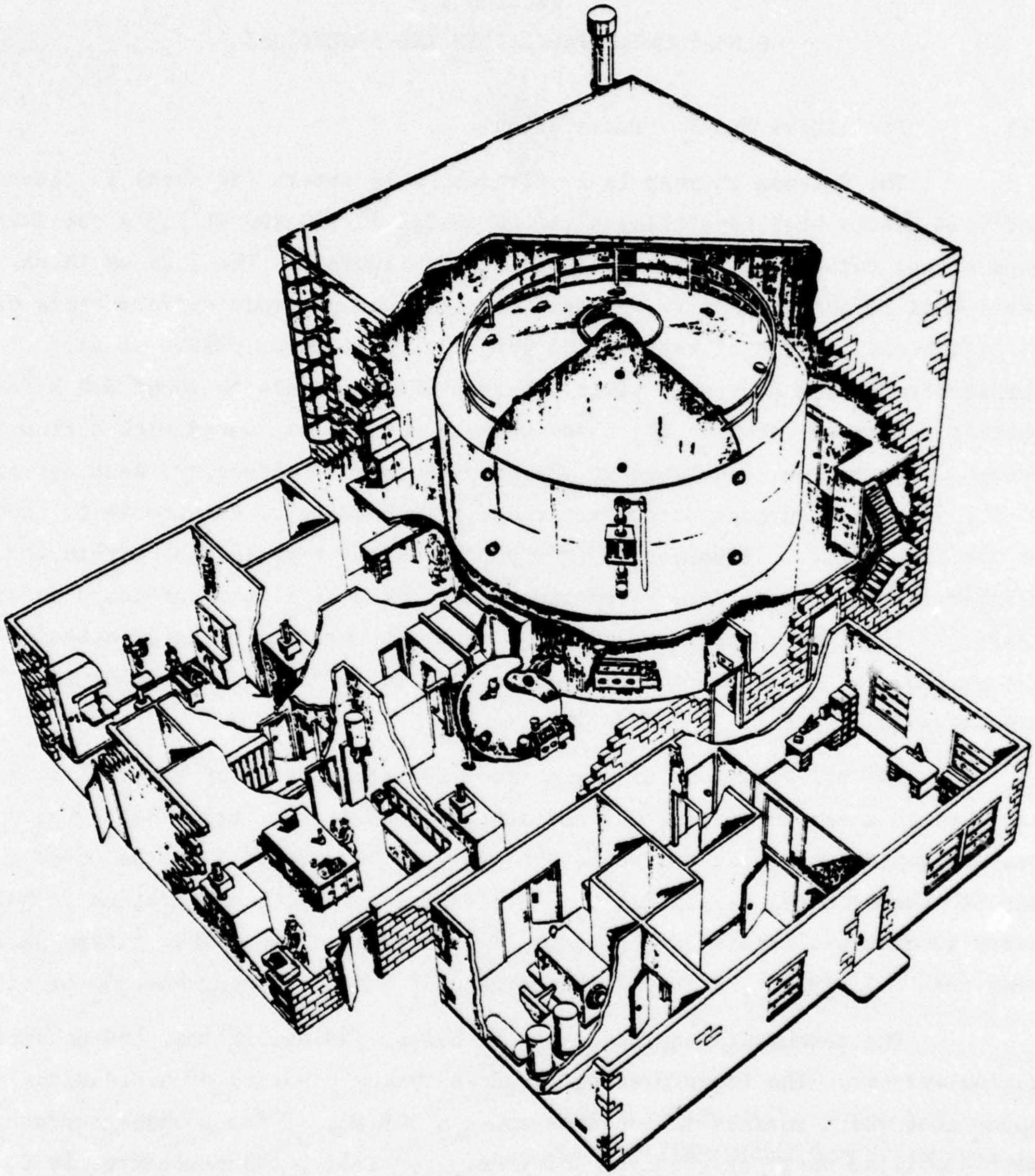


Figure 1 Cut-away View of Calspan's Chamber Facility

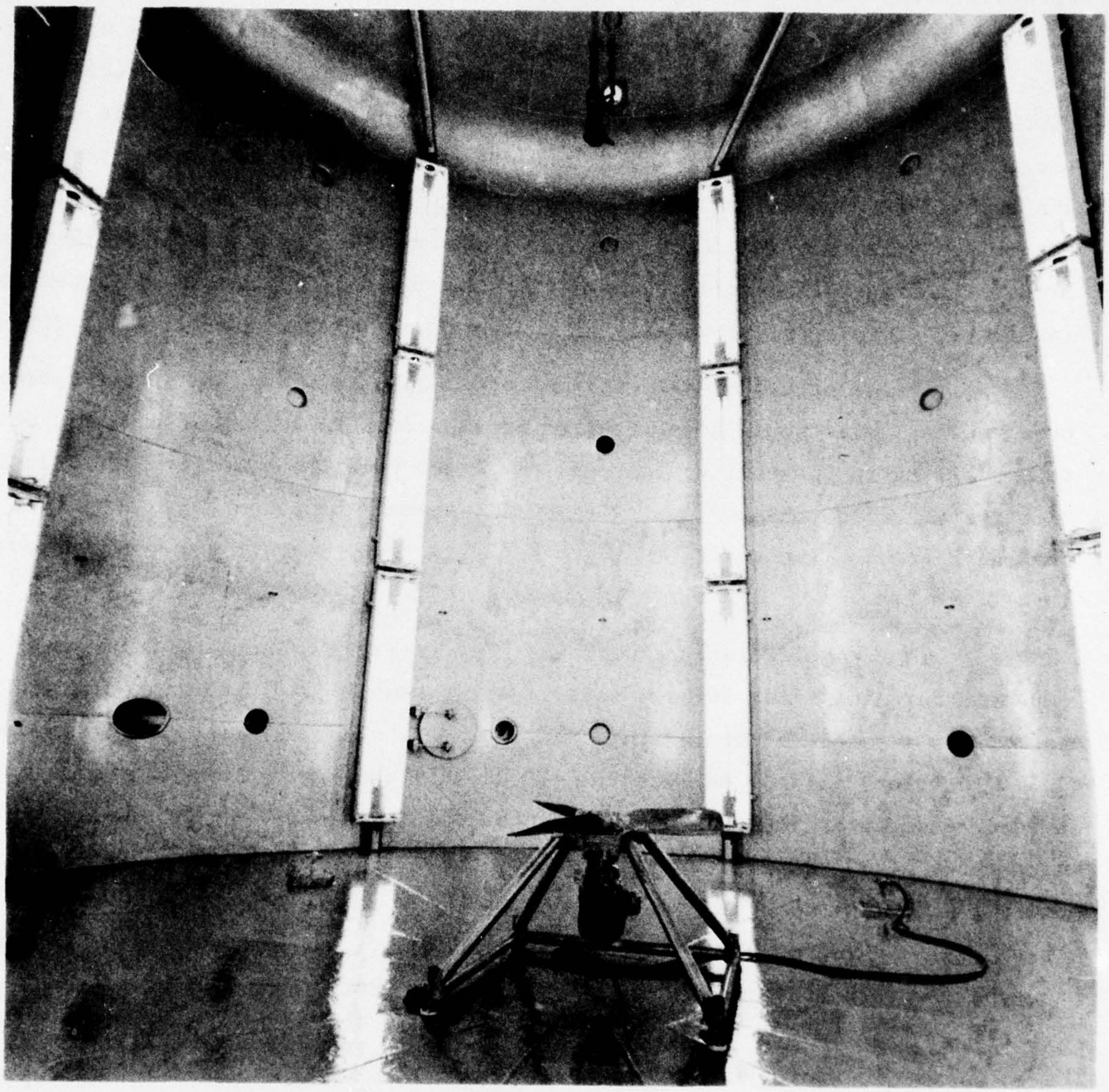


Figure 2 Inside view of Calspan's 600 m^3 Photochemical Aerosol Chamber

with distilled water. Drying is accomplished by fresh air flushing followed by air filtration. The washdown system is also used to wet the chamber wall prior to a cloud forming experiment. Chamber humidity is increased by spraying distilled water into the chamber from a remotely-operated spray nozzle near the chamber top. Nuclei which are introduced by the evaporating spray droplets are removed by absolute particle filters during the air filtration cycle. Chamber dehumidification, when needed, is accomplished by passing the chamber air over refrigeration coils to remove excess water. The system, designed and fabricated at Calspan, is capable of controlling humidity down to about 20% RH.

In the actual experiments performed on this study, dehumidification over cooling coils would have resulted in considerable losses of aerosols due to deposition on the coils. Instead, to reduce relative humidity, the illumination system of the chamber was switched-on, thereby heating the chamber by several degrees. Typically, relative humidity reductions of ∿5% were achieved in ∿20 minutes.

In aerosol-related experiments, an isokinetic sampling inlet is employed for minimizing aerosol losses during sampling. Instrumentation used to monitor aerosol behavior within the chamber include a Thermo Systems Model 3030 Electrical Aerosol Analyzer (EAA), an MRI Integrating Nephelometer, a Gardner Associates Small Particle Detector, a GE Condensation Nucleus Counter, Royco Models 220 and 225 Optical Particle Counters, and Calspan-built static thermal diffusion chamber (used to measure cloud condensation nuclei concentrations). In fog or haze experiments with significant concentrations of large aqueous droplets (>3 μm diameter), a Calspan droplet sampler is also used*.

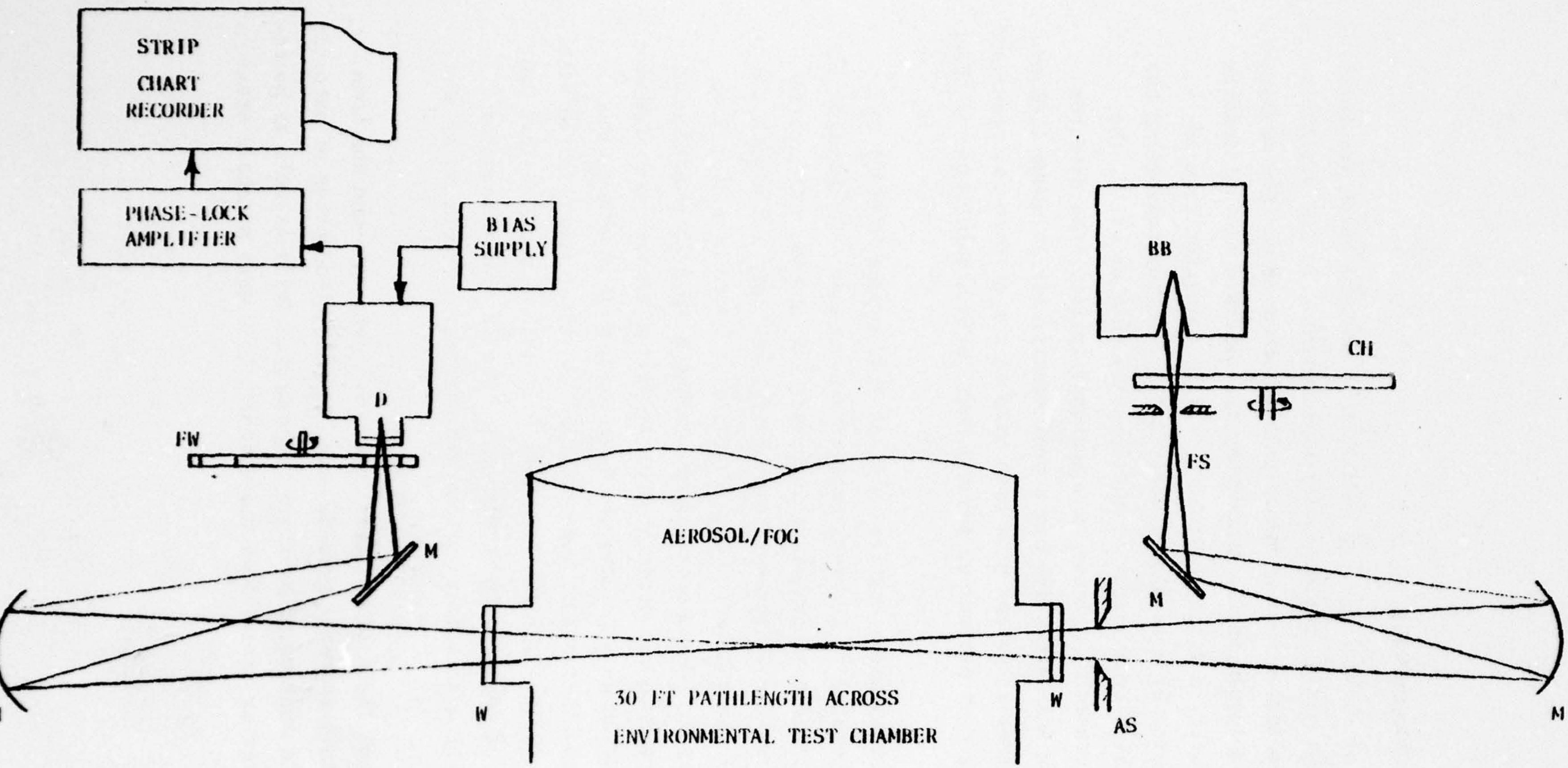
*The device impacts aqueous droplets onto glass slides coated with a thin film of gelatin. The resulting craters in the gelatin have been found to be nearly twice the diameter of the initial droplet, thus providing a measure of true drop diameter.

2.2 Extinction Measurements

Extinction of electromagnetic radiation by aerosol hazes was measured in the visible spectrum and at infrared (IR) wavelengths. In the visible range, light extinction was measured over a folded path of about 18 m. The measurements were made at two levels in the chamber by two separate transmissometer systems. For each system, a lense collimated the illumination from an incandescent bulb powered by a regulated power supply. After traversing the chamber twice (reflection by a mirror at the opposite chamber wall), the collimated beam was focused by a lense on a photomultiplier. The detector photomultiplier was an RCA-4440 which has a peak sensitivity at about 0.41 μm. The optical transmissometer systems have been used in the chamber for years and display good stability over periods of about 1 hour, with a resolution of about 2-3 percent.

The IR transmissometer utilized a black body source (900°C) and a BMDATC spectrometer operated at liquid nitrogen temperatures. To maximize the signal-to-noise ratio, the beam from the black body was chopped. Unlike the optical transmissometer, the IR transmissometer employed only a 9 m path length (i.e., one traverse of the chamber). The IR transmissometer is illustrated schematically in Figure 3. The chopped beam from the black body was focused through the chamber and onto the detector by a spherical front-silvered mirror. Observations of extinction as a function of wavelength were obtained with specific filters located in front of the detector. A filter wheel fitted with five bandpass filters (2.15, 3.7-3.8, 7.75-9.8, 9.13-10.33, and 13.5-16.1 μm) allowed the selection of specific IR wavelengths. The IR transmissometer exhibited good stability over 1 hour periods and offered a resolution of about 1 percent.

"Unattenuated" light intensities (i.e., I_o) were measured for both the visible and IR transmissometer systems prior to the introduction of aerosols into the chamber. As a measure of possible instrumental drift as well as potential deposition of water or aerosols on the windows, I_o's were measured after



LEGEND

D: HgCdTe DETECTOR
FW: FILTER WHEEL
M: MIRRORS
W: WINDOWS (KRS-5)

AS: APERTURE STOP
FS: FIELD STOP
CH: CHOPPER
BB: STANDARD BLACKBODY SOURCE

FIGURE 3 PRINCIPAL ELEMENTS OF THE IR TRANSMISSOMETER SYSTEM PRESENTLY DEPLOYED IN CALSPAN'S 600 M^3 CHAMBER

each experiment (subsequent to thorough flushing of the chamber). These measurements served as a base with which to gauge relative changes in light intensity due to interaction with the aerosol.

Estimates of extinction in terms of visibility were obtained from the optical transmission data using the well-known Bouguer law:

$$I = I_o \, e^{-\beta x}$$

where I_o is the intensity of the incident light, I is the observed light intensity at some distance x through the aerosol medium, and β is the composite scattering coefficient (b_{scat}) of the aerosol. Rather than present data in terms of optical visibility, results are presented with respect to visual range. Visual range is defined as the optical path length required to produce 98 percent extinction of the incident light. Based upon this definition, the composite b_{scat} is related to the visual range (V) by the relation

$$b_{scat} = \frac{3.912}{V}.$$

Throughout the text, visibility and visual range will be used interchangeably. According to this general definition, we can discuss the visual range interchangeably with b_{scat} at all wavelengths of electromagnetic radiation, not necessarily confined to the visible spectrum.

2.3 Haze and Fog Generation

Production of the pyrotechnic hazes/fogs was accomplished as follows: After humidification of the chamber to greater than the desired relative humidity using a commercial nebulizer, all particulates were removed by absolute filters. The filtration process usually resulted in a decrease of relative humidity of about 5%. Subsequently, a specific quantity of the pyrotechnic (Salty Dog) was burned in the chamber. Due to the hygroscopic nature of the resulting pyrotechnic

smoke, the individual aerosol particles absorbed water until the vapor pressure of the concentrated aqueous droplets equalled that of the ambient air, producing a haze whose density at a given relative humidity was dependent upon the quantity of pyrotechnic burned.

Water droplet fogs were produced in the chamber by expansion of near-saturated air. Initially, the chamber was humidified to near-saturated conditions by wetting the entire inner surface with distilled water using a remotely-controlled spray nozzle. With the relative humidity in the chamber typically in excess of 95% following the washdown, the chamber was pressurized to about 2.9 kilopascals (30 cm of water) relative to atmospheric pressure. The pressurized state was maintained for about 15 minutes to restore equilibrium temperature conditions and permit further evaporation from the wet chamber walls. During this period, nuclei of the desired composition (in some instances, salty dog) were introduced into the chamber to serve as condensation sites for fog formation. At the end of the equilibration period, pressure was decreased within the chamber by withdrawing air at a metered rate. Initially, the pressure was dropped abruptly to produce a state of supersaturation which activated the fog nuclei and secured the desired growth of the fog droplets. Afterwards, a continuous pressure reduction was required to maintain the fog by negating the effects of heating from the warm chamber walls.

In the salty dog haze/fog experiments, the pyrotechnic was aerosolized by burning. To provide consistent burns as well as to provide a means of coating the aerosols with stabilizing material in later experiments, the pyrotechnic was ignited by a propane torch at the base of a 1 m long, 15 cm (I.D.) stack. Virtually all of the smoke from the burn was carried upward through the stack, its vertical motion induced by convection. During stabilization experiments, vapors of stabilizing material (i.e., cetyl alcohol) were carried by compressed air and introduced into the pyrotechnic smoke near the base of the stack. Subsequent mixing with and coating of the pyrotechnic aerosol was expected to occur in the stack.

Section 3
EXPERIMENTAL RESULTS

The objectives of this limited experimental program were to provide an evaluation of the efficiency of certain pyrotechnic aerosols in producing conditions of restricted visibility at subsaturated humidities and the influence of an evaporation retardant, cetyl alcohol, in prolonging the lifetime of such artificial fogs at lower relative humidities. In a typical experiment, a haze/fog was generated in Calspan's chamber by burning a prescribed quantity of the pyrotechnic material under prescribed humidity conditions. After the cloud stabilized and its characteristics measured, relative humidity in the chamber was lowered and the response of the fog was monitored. In companion experiments, cetyl alcohol vapors were mixed with the pyrotechnic aerosols immediately upon generation in a "mixing chamber" prior to being vented into the chamber; again the treated fog was monitored as relative humidity was lowered. In each experiment, continuous measurements of extinction coefficient (visibility) at both visible and infrared wavelengths, relative humidity and complete aerosol size spectra (0.01 to 10.0 μm diameter) were obtained. Visibility data provided information on "yield" as a function of pyrotechnic payload, on the stability of the pyrotechnic hazes/fogs, and on the effectiveness of an evaporation retardant in prolonging the lifetime of the artificial fogs.

The basic aerosol used for producing conditions of restricted visibility at subsaturated humidities in these experiments was generated by pyrotechnic devices known as "Salty Dogs." The devices developed at the Naval Weapons Center (Hindman and Heimdahl, 1977) are said to be composed of "18% hydrocarbon binder, 5% magnesium, 10% sodium chloride, 65% potassium perchlorate and 2% lithium carbonate." When burned, the pyrotechnic produces copious quantities of hygroscopic aerosol ($\sim 10^{11}$ particles>0.5 μm diameter per gram of material, according to Hindman and Heimdahl). The pyrotechnics used by Calspan

were supplied by the Naval Weapons Center at China Lake through the auspices of Dr. L. H. Ruhnke of the Naval Research Laboratory, and the support of Dr. Ruhnke is gratefully acknowledged.

In the design phase of the laboratory investigation, it was desired that the experiments be conducted with aerosol concentrations ranging from that observed in the natural marine environment (i.e., 1-50 cm^{-3})* to several orders of magnitude greater. Based on the data of Hindman and Heimdahl, it was decided to conduct specific experiments with three different quantities of the pyrotechnic: 0.1 g ($\pm$0.01 g), 1.0 g ($\pm$0.06 g), and 6.0 ($\pm$0.08 g)--corresponding to aerosol concentrations for particles >0.5 μm diameter of $\sim$17 cm^{-3}, $\sim$170 cm^{-3}, and 10^3 cm^{-3}, respectively, for our chamber volume. To maintain consistent aerosolization in our experiments, the Salty Dog pyrotechnic was aerosolized by "forced burning"--i.e., the flame from a propane torch was directed onto the pyrotechnic, even though it would burn freely, until it was completely consumed.

3.1 Results of the Experiments

A total of 16 pyrotechnic-fog and 3 water-droplet (natural) fog experiments were conducted on this program. (Visibility and relative humidity records and aerosol spectra, where available, are provided for each experiment in Appendix A.) In addition, limited data were acquired in 6 preliminary experiments conducted during the design and instrumentation check-out phases of this program. In each experiment a prescribed quantity of pyrotechnic was burned at a prescribed relative humidity (RH), and the resultant aerosol fog was allowed to reside for $\sim$6-10 minutes before RH was changed. The visibility records from a typical experiment (#12) are reproduced in Figure 4. In Experiment #12, 5.97 g of Salty Dog were burned at 96% RH, and visibility

*e.g., Mack, et al. (1978)

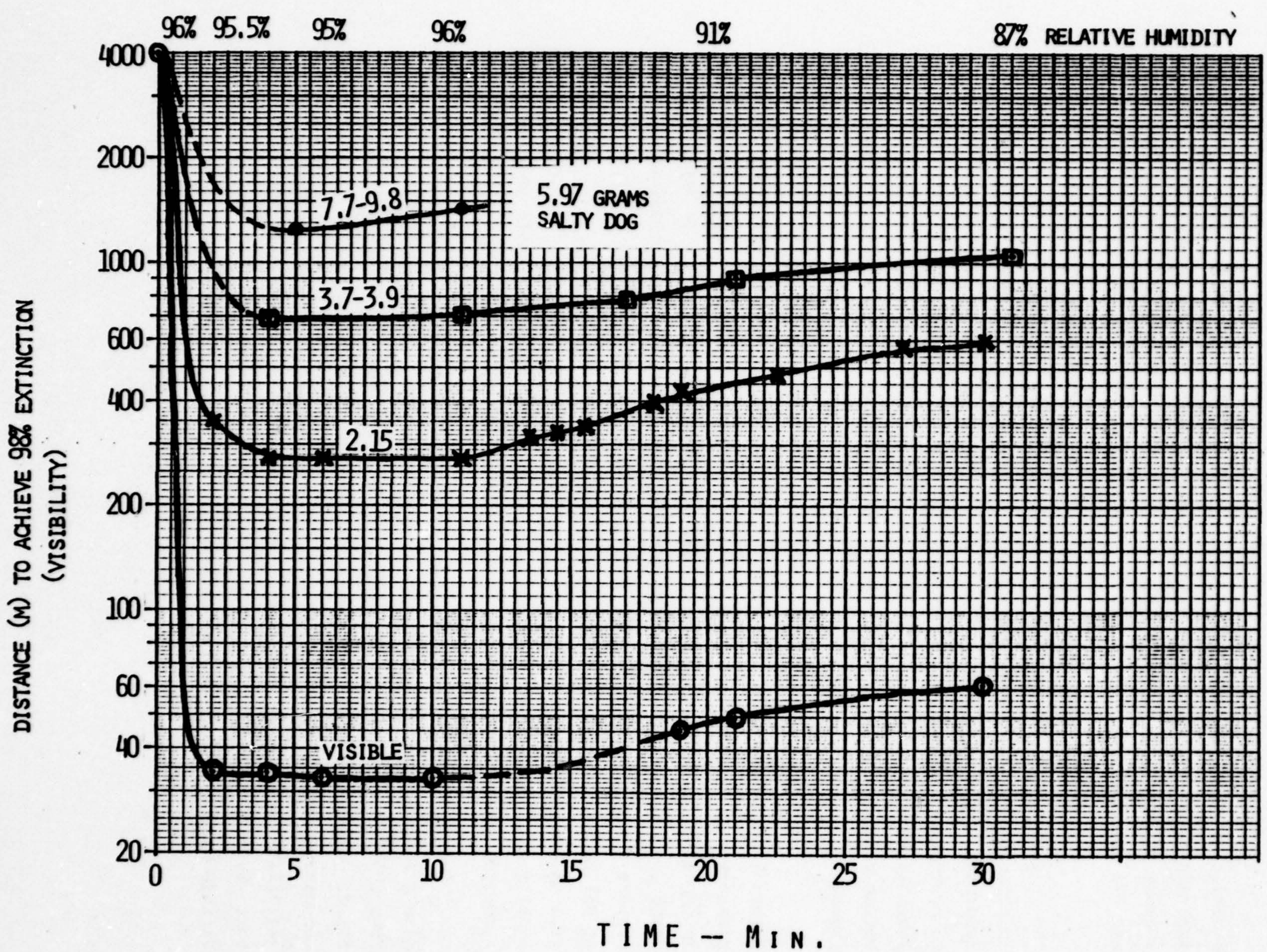


Figure 4: Visibility at Four Wavelengths as Functions of Time in Experiment #12 (5.97 g Salty Dog Burned at 96% RH; RH subsequently lowered to 87%)

immediately degraded to minimum values (∿35 m at visible wavelengths), remaining relatively constant (with constant RH) through the next 10 minutes. Subsequent reduction in RH beginning at t = ∿11 minutes brought about inprovement in visibility.

Pertinent parameters for the initial 6-10 minute periods in each of the 16 experiments are provided in Tables 1 and 2. Table 1 provides general information on the type of experiment, quantity of pyrotechnic burned, RH, resultant visibility restriction (visible wavelengths) and total particle concentration. Table 2 provides specific data on visibilities at four wavelengths, aerosol concentration at three size intervals and total aerosol volume produced by burning the specified quantities of pyrotechnic in Calspan's chamber.

It is readily seen from the data presented in Tables 1 and 2 and Figure 4 that dense fogs were produced as a result of burning the Salty Dog pyrotechnics. It is also evident that the density of the fogs was dependent, as expected, on both the quantity of pyrotechnic and RH, much more dense fogs being produced at higher relative humidities. The pyrotechnic produced copious quantities of aerosols, the outputs ranging from 10^4 cm^{-3} for 0.1 g at 45% RH to 3×10^5 cm^{-3} for 6.0 g at 95% RH. The concentrations of aerosols >1.0 μm diameter ranged from 1 cm^{-3} to ∿3500 cm^{-3} for the same range of experimental conditions. The measured aerosol concentrations were in good agreement with expected values (based on the results of Hindman and Heimdahl).

In addition to extinction at visible wavelengths, Salty Dog aerosols also produced some extinction at longer wavelengths in some experiments (e.g., Figure 4). The data presented in Table 2 show visibility reductions at 2.15 μm for all experiments in which the pyrotechnic payload was ∿1.0 g or greater and concentrations of aerosols >1.0 μm diameter were >85 cm^{-3}. (Maximum detectable visibility restriction with our IR instrumentation was ∿4000 m.) Note, however, that visibilities at 2.15 μm were a factor of ∿5-10 greater than those in the visible wavelength. Likewise, visibility restrictions were observed at the

Table 1

Complete Log of Primary Pyrotechnic and Water Droplet Fog Experiments

Expt. No.	Salty Dog Payload	Experiment Type	Initial RH	RH at t=8 min	Minimum Visibility (Visible Wavelength)	Total Particle Concentration
1	0.09 g	Constant RH	45%	45%	26.5 km	1.1×10^4 cm^{-3}
2	0.10	Constant RH	58	59	25.0 km	1.1×10^4
3	0.11	Increase RH	65	67	18.0 km	2.0×10^4
4	0.10	Lower RH	80	80	6.3 km	1.5×10^4
5	0.11	Lower RH	80	80	5.8 km	3.0×10^4
6	0.09	Lower RH	97	97	1.1 km	2.3×10^4
7	0.10	Constant RH	98	98	0.5 km	2.4×10^4
8	1.06	Lower RH	79	78	520 m	7.0×10^4
9	1.05	Constant RH	81	82	480 m	7.5×10^4
10	1.04	Lower RH	96	96	140 m	7.5×10^4
11	5.96	Lower RH	80	79	85 m	2.5×10^5
12	5.97	Lower RH	96	95	35 m	3.0×10^5
13	5.95	Constant RH	99	99	< 20 m	-
14	0.94	Cetyl Alch.; Lower RH	97	97	125 m	8.5×10^4
15	6.08	Cetyl Alch.; Lower RH	80	82	75 m	4.0×10^5
16	6.07	Cetyl Alch.; Lower RH	96	96	25 m	3.2×10^5
17	-	Simulated "Polluted" Fog	-	100	25 m	-
18	-	Simulated "Inland" Fog	-	100	40 m	-
19	-	Simulated "Marine" Fog	-	100	90 m	-

Table 2

Initial Visibilities at Four Wavelengths, Particle Concentrations at Three Size Intervals and Total Volume of Aerosol Produced in Pyrotechnic-Fog Experiments

			Minimum Visibility At Indicated Wavelength					Particle Concentration at Sizes > Indicated Diameter				Amount of Aerosolized Material in 590 m^3 Chamber		
Expt. No.	Amount Burned (g)	RH (%)	Visible (m)	2.15 (m)	3.7-3.9 (m)	7.7-9.8 (m)	9.1-10.3 (m)	>0.01μm (cm^{-3})	>0.1μm (cm^{-3})	>1.0 μm (cm^{-3})	>5.0 μm (cm^{-3})	Volume (cm^3)	Mass ρ=1 (g)	Mass ρ=2 (g)
1	0.09	45	$2.7x10^4$	-	-	-	-	$1.1x10^4$	$2.0x10^3$	1	0	$4.3x10^{-3}$	.004	.009
2	0.10	58	$2.5x10^4$	-	-	-	-	$1.1x10^4$	$3.4x10^3$	2	0	$1.0x10^{-2}$	.010	.02
3	0.11	66	$1.8x10^4$	-	-	-	-	$2.0x10^4$	$2.7x10^3$	3	0	$0.9x10^{-2}$	.009	.02
4	0.10	80	$6.3x10^3$	-	-	-	-	$1.5x10^4$	$5.4x10^3$	16	0	$3.9x10^{-2}$	.039	.08
5	0.11	80	$5.8x10^3$	-	-	-	-	$3.0x10^4$	$5.5x10^3$	40	0	0.11	.11	.22
6	0.09	97	$1.1x10^3$	-	-	-	-	$2.3x10^4$	$6.5x10^3$	85	0	0.22	.22	.44
7	0.10	98	$0.5x10^3$	-	-	-	-	$2.4x10^4$	-	-	-	-	-	-
8	1.06	79	520	$2.7x10^3$	-	-	-	$7.0x10^4$	$4.0x10^4$	330	0	0.77	.77	1.5
9	1.05	81	480	$2.5x10^3$	-	-	-	$7.5x10^4$	$4.5x10^4$	280	0	0.65	.65	1.3
10	1.04	96	140	300	520	$3.5x10^3$	-	$7.5x10^5$	$4.5x10^4$	600	0	1.49	1.49	3.0
11	5.96	79	85	$1.5x10^3$	-	-	-	$2.5x10^5$	$1.5x10^5$	2000	0	5.81	5.81	11.6
12	5.97	95	35	270	700	$1.2x10^3$	-	$3.0x10^5$	$2.2x10^5$	3000	0	9.1	9.1	18.2
13	5.95	99	< 20	?	?	?	600	-	-	-	-	-	-	-
14	0.94	97	125	?	?	?	-	$8.5x10^4$	$4.7x10^4$	1000	0	2.47	2.47	4.9
15	6.08	81	75	$1.2x10^3$	$3.8x10^3$	-	-	$4.0x10^5$	$1.8x10^5$	3400	0	16.5	16.5	33.0
16	6.07	96	25	95	250	950	-	$3.2x10^5$	$2.1x10^5$	3700	0	19.3	19.3	38.6
17	Fog	100	25	?	?	?	30	-	-	3200	1145	205	205	-
18	Fog	100	40	?	?	?	45	-	-	-	-	-	-	-
19	Fog	100	90	?	?	?	30	-	-	100	100	140	140	1

7.7-9.8 μm wavelength when concentrations of aerosols of >1.0 μm diameter were >∿400 cm^{-3}. Visibilities at 7.7-9.8 μm wavelength were a factor of 25-40 greater than those in the visible spectrum. The data indicate, as expected, that extinction was wavelength and particle size dependent.

The dependence of extinction at IR wavelengths on particle size is graphically illustrated, and distinguished from that observed in the pyrotechnic aerosol fogs, by data obtained in three "natural" water-droplet fogs produced during this series of experiments. The data are shown as Experiments 17, 18 and 19 in Tables 1 and 2 and Appendix A. The fogs, produced as described in Section 2, accurately mimicked natural fogs, in that they were comprised of relatively high concentrations of large (i.e., >∿3 μm diameter) water droplets. Mean droplet diameters in Fog Experiments 17 and 19 were, respectively, ∿6 μm and ∿18 μm, while the pyrotechnic fogs described in this report were comprised primarily of near-saturated solution droplets <5 μm diameter. Note that while only minimal extinction was observed at IR wavelengths in the pyrotechnic fogs (Table 2), IR extinction (at ∿10 μm wavelength) matched or surpassed the extinction observed in visible wavelengths in the "natural" fogs. In addition to extinction by scattering, the aqueous fog droplets will absorb portions of the incident radiation at wavelengths greater than 2.5 μm. In the case of the IR transmissometer data, absorption may represent a significant contribution to the total extinction by "natural" fogs. These results demonstrate the potential extinction of IR possible through judicious choices of aerosol size, concentration, and composition.

The per-gram "yields" of the Salty Dog pyrotechnics, in terms of numbers of particles, aerosol volume and extinction coefficient are summarized in Table 3. The per-gram output of aerosols at various size intervals (Table 3) shows that total aerosol concentrations for size ranges >0.01 μm and >0.1 μm diameter were similar for all experiments (within a factor of 2 of the mean) and relatively insensitive to payload size or RH. However, the concentration of particles of size >1.0 μm appeared to be relative humidity dependent, with average values at 95-97% RH being a factor of 40 greater than concentrations at RH < 67%. This humidity dependence was due to the growth of the hygroscopic particles originally smaller than 0.1 μm by the absorption of water with increasing relative humidity.

Table 3

The Yield Per Gram of Aerosols as a Function of Particle Size and Relative Humidity, of Total Aerosol Volume, and of Composite Extinction for "Salty Dog" Pyrotechnics

Experiment No.	RH	Particles/gram of Size >Indicated Diameter >0.01 μm	>0.1 μm		>1.0 μm	Total Aerosol Volume (per gram)	Composite Extinction At Visible Wavelength (per gram)
1	45%	7.2×10^{13}/g	1.3×10^{13}/g		0.7×10^{10}/g	0.048cm^3/g	1.64 km^{-1}
2	58%	6.5×10^{13}	2.0×10^{13}		1.1×10^{10}	0.100	1.57
3	66%	10.7×10^{-13}	1.4×10^{13}		1.6×10^{10}	0.082	1.98
4	80%	8.9×10^{13}	3.2×10^{13}		9.4×10^{10}	0.390	6.21
5	80%	16.1×10^{13}	3.0×10^{13}		21.5×10^{10}	1.00	6.13
6	97%	15.1×10^{13}	4.3×10^{13}		55.7×10^{10}	2.44	35.56
8	79%	3.9×10^{13}	2.2×10^{13}		18.4×10^{10}	0.726	7.09
9	81%	4.2×10^{13}	2.5×10^{13}		15.7×10^{10}	0.619	7.76
10	96%	4.3×10^{13}	2.5×10^{13}		34.0×10^{10}	1.433	26.87
11	79%	2.5×10^{13}	1.5×10^{13}		19.8×10^{10}	0.975	7.72
12	95%	3.0×10^{13}	2.2×10^{13}		29.6×10^{10}	1.524	18.72
14	97%	5.3×10^{13}	3.0×10^{13}		62.8×10^{10}	2.628	33.29
15	81%	3.9×10^{13}	1.7×10^{13}		33.0×10^{10}	2.714	8.58
16	96%	3.1×10^{13}	2.0×10^{13}		36.0×10^{10}	3.180	25.78
Average		6.8×10^{13}	2.4×10^{13}	(RH < 67%)	1.1×10^{10}	0.077	1.73
(all RH)				(RH 79-81%)	19.6×10^{10}	0.975	7.25
				(RH 95-97%)	43.6×10^{10}	2.241	28.04

Similarly, total aerosol volume per gram and the per gram composite extinction (Table 3) were found to be quite consistent for identical experimental parameters (e.g., compare Experiments 1 and 2, 8 and 9, or 11 and 15). However, a marked dependence on relative humidity of the per-gram yields of aerosol volume and composite extinction was observed (e.g., compare Experiments 2, 4 and 6, 9 and 10, 11 and 12, or 15 and 16). The data indicate that expected visibilities from a cloud of pyrotechnically generated Salty Dog aerosols should be dependent on both the amount of material dispensed and on the relative humidity.

The above conclusion is completely supported by the data presented in Figure 5. In Figure 5, measured visibilities (visible wavelength data from stable periods in all of the tests including preliminary experiments and the periods of reduced RH in Experiments 1-16) are plotted as a function of relative humidity for each Salty Dog payload. These data demonstrate the marked dependence of visibility on both the amount of airborne pyrotechnic and ambient RH. Note that resultant visibilities at given RH for 1.0 and 6.0 g payloads were $\sim$1/10 and $\sim$1/60, respectively, of that for the 0.1 g payload. It is also evident that burning at reduced relative humidity resulted in visibilities approximately a factor of 2 greater for a reduction in RH by $\sim$10%. These data could be used to estimate plume centerline visibilities in atmospheric tests for given airborne concentrations (i.e., 1.0×10^{-2}, 1.7×10^{-3} and 1.7×10^{-4} g/m^3), providing that aerosolization (forced burn) techniques are similar to those used in these experiments.

3.2 Stability and Stabilization of Salty Dog Aerosol Fogs

In the marine atmosphere, relative humidity can change as a result of diurnal influences, radiative processes, advection over a sea surface of different temperature, vertical mixing and synoptic processes. Obviously over time scales of the order of 24 hours, relative humidity can change by tens of percent. However, for shorter periods (of the order of 1 hour) when screens can be reasonably expected to be effective, relative humidity changes will be relatively minor (i.e., of the order of 5-10%). Aloft, RH can decrease or increase with height by tens of percent depending on specific circumstances;

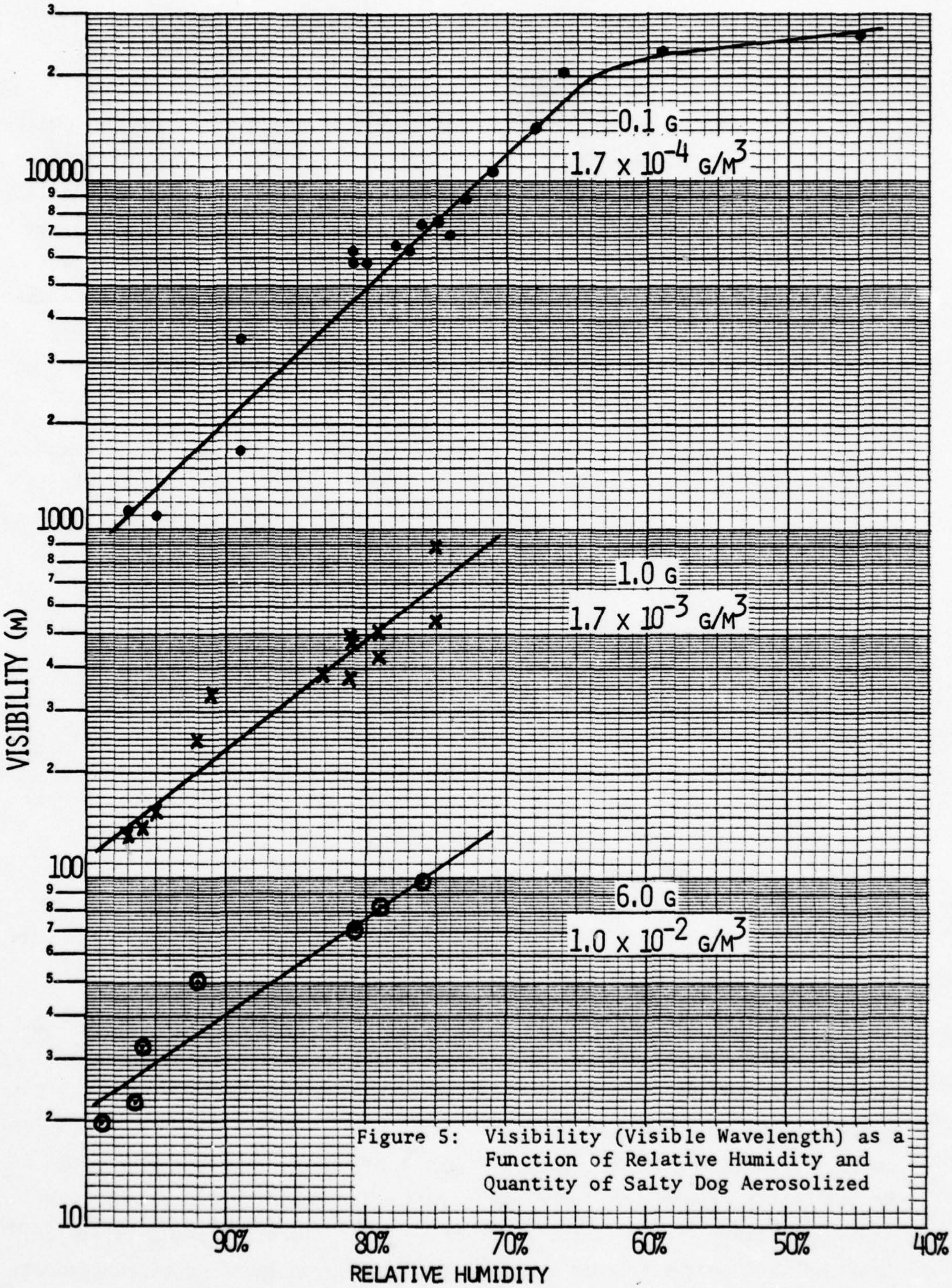


Figure 5: Visibility (Visible Wavelength) as a Function of Relative Humidity and Quantity of Salty Dog Aerosolized

low-level marine boundary layer inversions will typically be accompanied by increasing RH with height up to the base of the inversion and decreasing RH above the inversion base (e.g., Mack et al., 1974, 1975 and 1978).

Of prime concern in this investigation was the stability of the Salty Dog aerosol fogs--i.e., the ability of the cloud to remain an effective screen when exposed to lower relative humidities. Specific data on the output characteristics of Salty Dog pyrotechnic aerosol fogs was summarized in the preceding section and showed that, for relative humidity differences of 10%, resultant visibilities differed by a factor of ∿2 (in the visible wavelengths). In Figures 6 through 10 the visibility records (both visual and IR wavelengths) for Experiments 5, 8, 11, 10 and 7, respectively, are shown. Each figure is annotated with information concerning pyrotechnic payload and relative humidity as a function of time during the respective experiments.

Figures 6, 7 and 8 show, respectively, visibility records for experiments in which 0.1, 1.0 and 6.0 g payloads of Salty Dog were burned at ∿80% RH and in which RH was lowered to ∿74% within 30 minutes of the burn. Note that lowest visibilities were achieved, as expected, at visible wavelengths and for the greater quantities of pyrotechnic. Some improvement in visibility is also evident as RH was lowered in the experiments.

Figures 9, 10 and 4 show, respectively, visibility records for a similar set of experiments (#s 6, 10 and 12) conducted with initial RH in the range 95-97%. Note again that visibility restriction was progressively greater for greater quantities of pyrotechnic and substantially greater than that for the 80% RH experiments shown in Figures 6-8. Again, visibilities improved when RH was reduced.

An objective of this laboratory investigation was an assessment of the feasibility of applying an evaporation retardant, cetyl alcohol, to the Salty Dog aerosols for improving the stability of the pyrotechnic aerosol fogs. Three such formal experiments (#s 14, 15 and 16) were conducted, and the visibility records for Experiment #15 are reproduced in Figure 11. The extent of coating of the aerosol particles by the ∿0.1 g of cetyl alcohol used during each of the stabilized

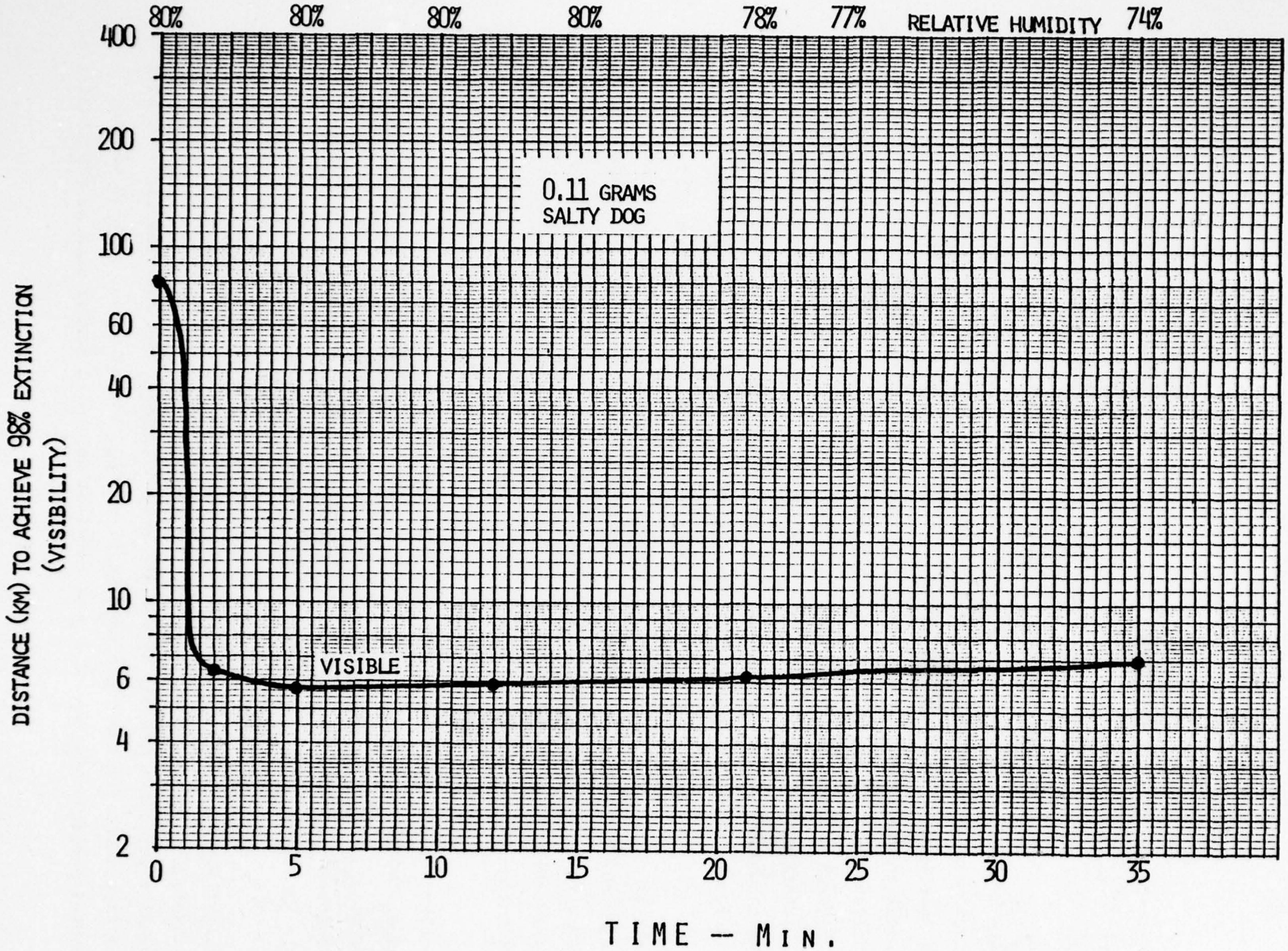


Figure 6: Visibility as a Function of Time in Experiment #5

(Integrating Nephelometer data in km)

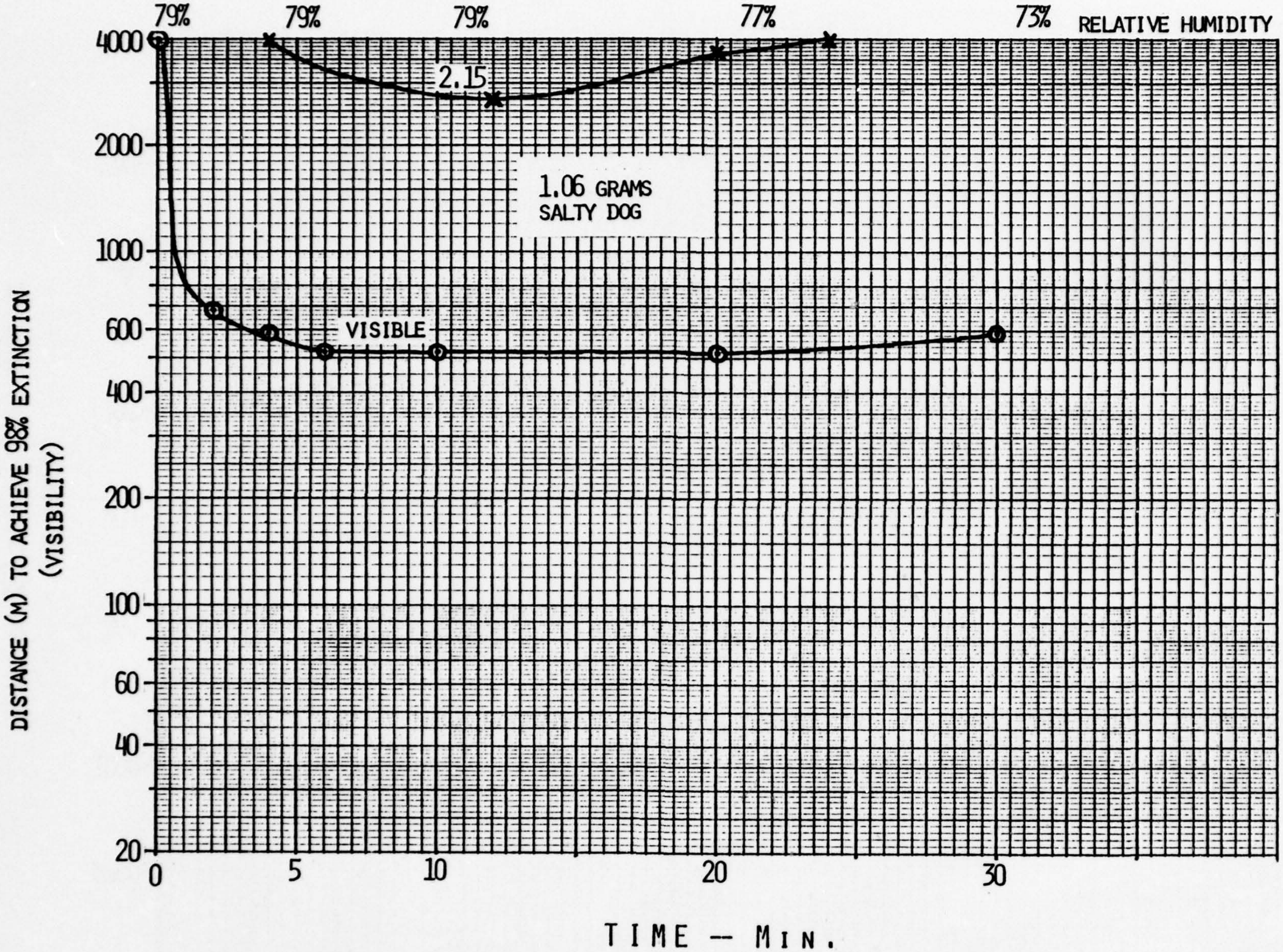


Figure 7: Visibility as a Function of Time in Experiment #8

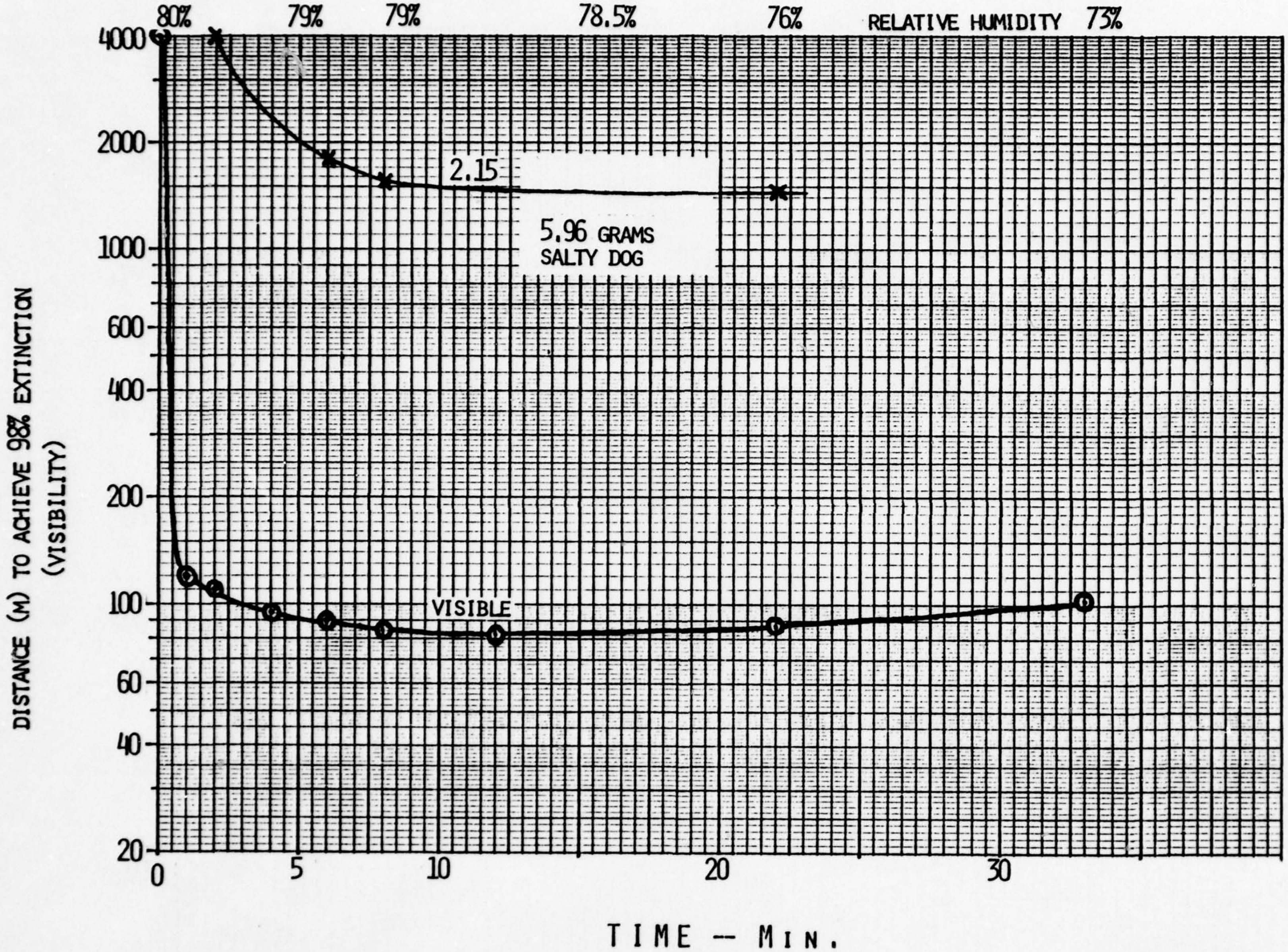


Figure 8: Visibility as a Function of Time in Experiment #11

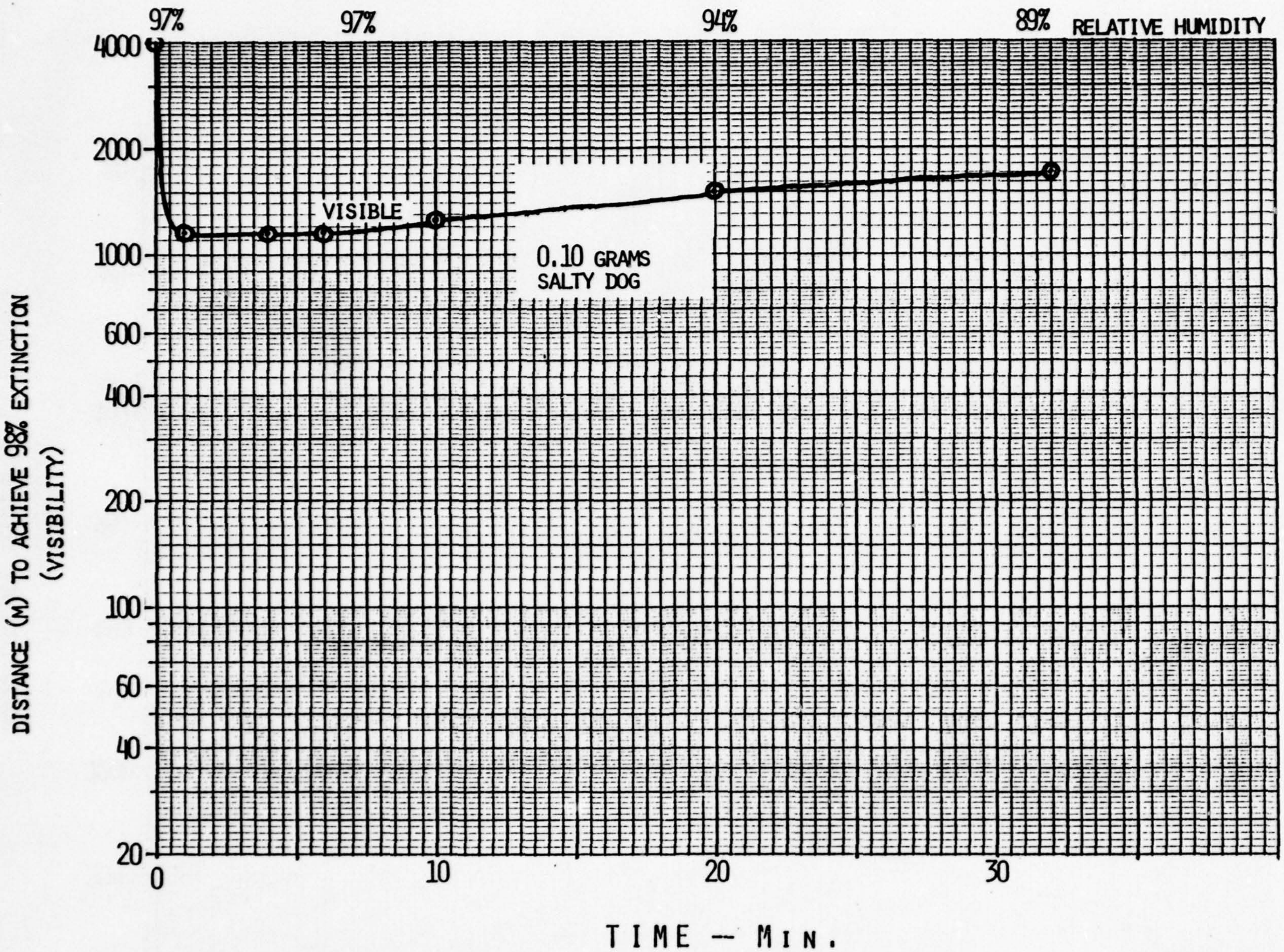


Figure 9: Visibility as a Function of Time in Experiment #6

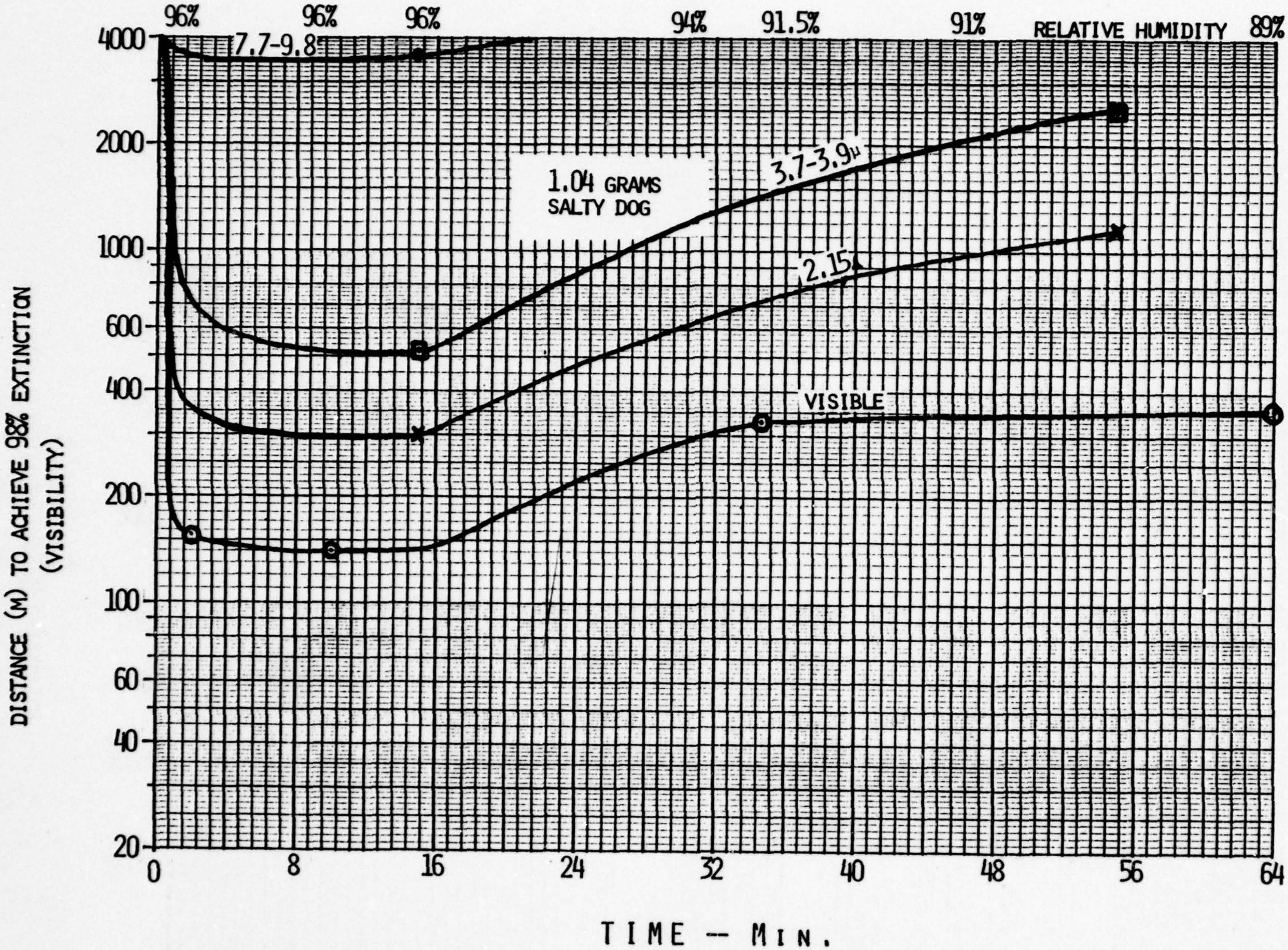


Figure 10: Visibility as a Function of Time in Experiment #10

experiments is unknown. (Data for Experiments 14 and 16 may be found in Appendix A.) Note that the visibility levels and trends for this 6 g/81% RH experiment were similar to those of Experiment 11 (Figure 8) in which cetyl alcohol was not used.

The changes in visibility observed as functions of relative humidity in the aforementioned experiments may be ascribed to the hygroscopic nature of the Salty Dog aerosols. Apparently, at RH >65% (see Figure 5), the Salty Dog aerosols are aqueous solutions whose vapor pressure is at equilibrium with the environment. The relationship between particle radius r at a given relative humidity and the particle radius r_o at zero percent relative humidity is given by

$$\frac{r}{r_o} = [1 + \frac{\sigma}{1-S}]^{1/3}$$

where σ = 1.22 for NaCl droplets and S is the saturation ratio. The growth of an aerosol spectrum with increasing RH is demonstrated by the data presented in Figure 12*. Figure 12 shows successive aerosol spectra measured in Experiment #3 while relative humidity was increased from 65 to 81% over a 40 minute period. Visibility in this 0.1 g experiment degraded from 20 to ~6 km during the period (see #3 in Appendix A).

Similar aerosol size spectra as functions of relative humidity for individual experiments are shown for 0.1, 1.0 and 6.0 g Salty Dog payloads in Figures 13, 14 and 15, respectively. Note that the 81% RH spectrum for Experiment #4 ("C" in Figure 13) is nearly identical to that at 81% RH in Experiment #3 ("F" in Figure 12). When the overlap range (0.1 to 0.5 μm) of the two aerosol characterization devices (EAA and Royco) are disregarded as in Figures 12, 13, 14, and 15, similar aerosol growth is indicated for both large and small particles. Such behavior suggests uniformity of aerosol composition for all particle sizes. Calculations of aerosol growth (assuming NaCl aerosol) as a function of relative humidity account for only a portion of the observed growth. The unknown composition of the actual aerosol makes such modeling difficult.

*The portion of the aerosol spectra (>0.1 μm and < 0.5 μm diameter) where the two aerosol sampling devices overlap are not shown. Typically, the first and last size intervals measured by these types of instruments are not as accurate as are their respective middle size intervals.

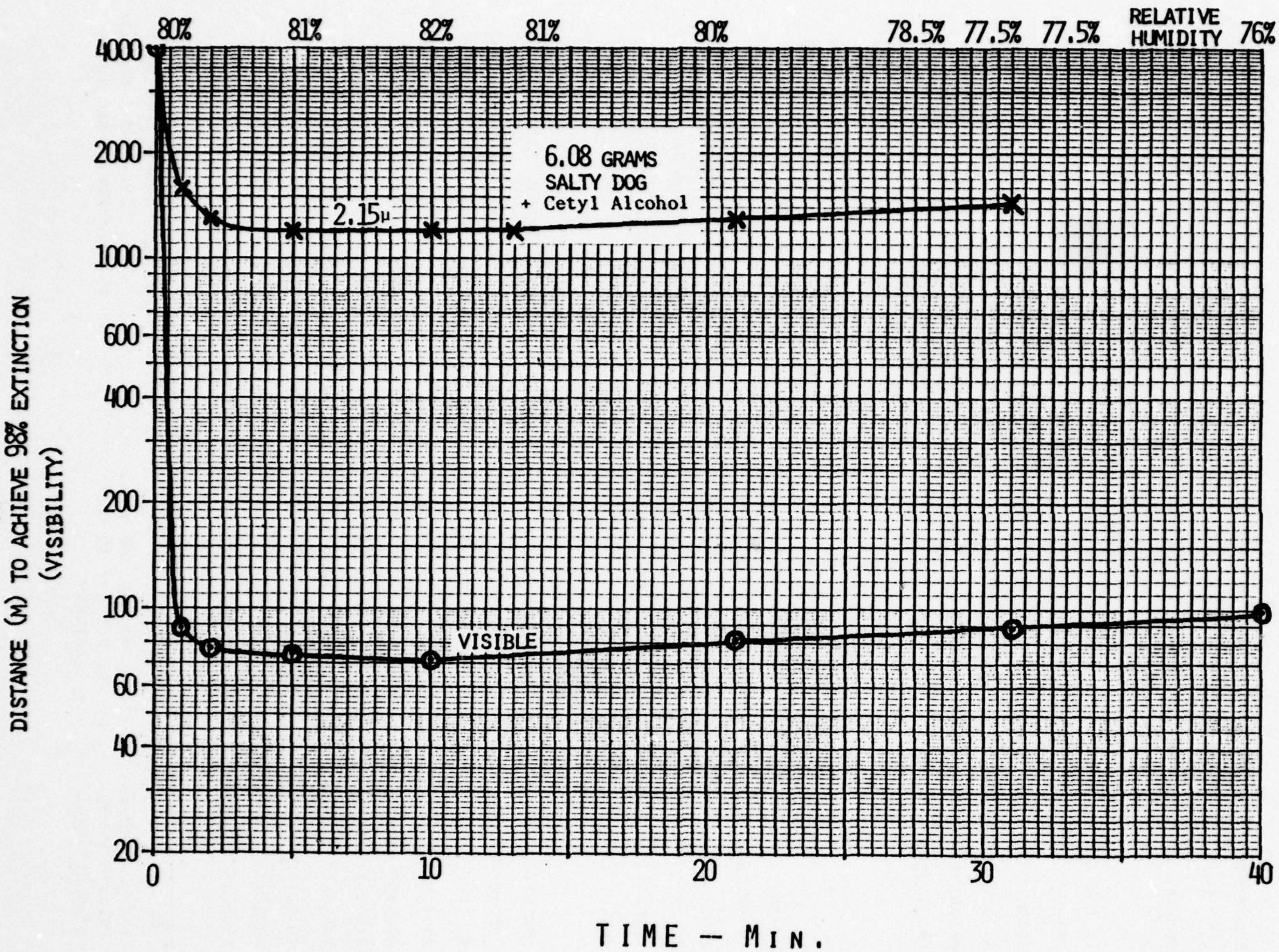


Figure 11: Visibility as a Function of Time in the Cetyl Alcohol Treated Aerosol Fog Experiment #15

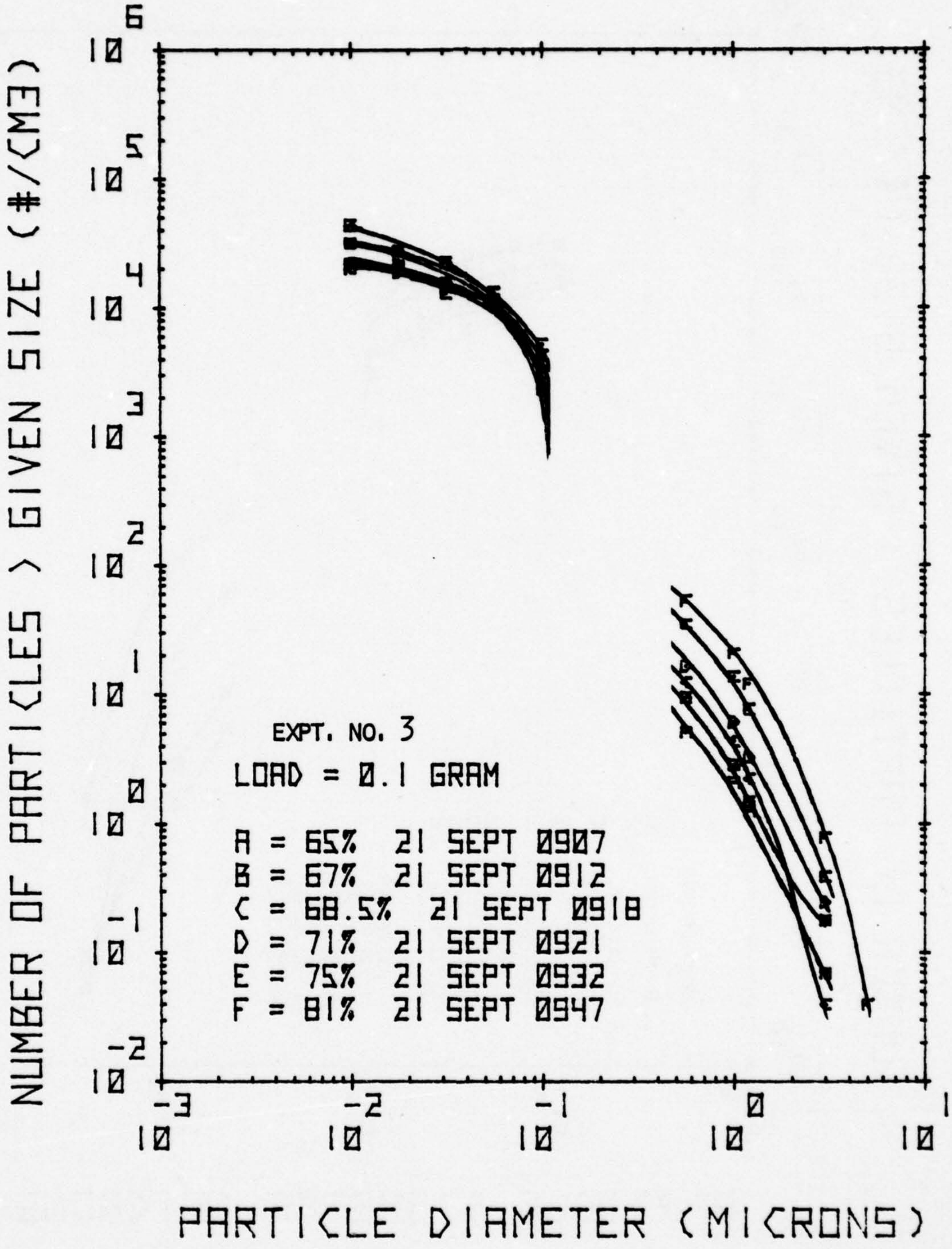


Figure 12: Aerosol Size Spectra as a Function of Relative Humidity in Experiment #3

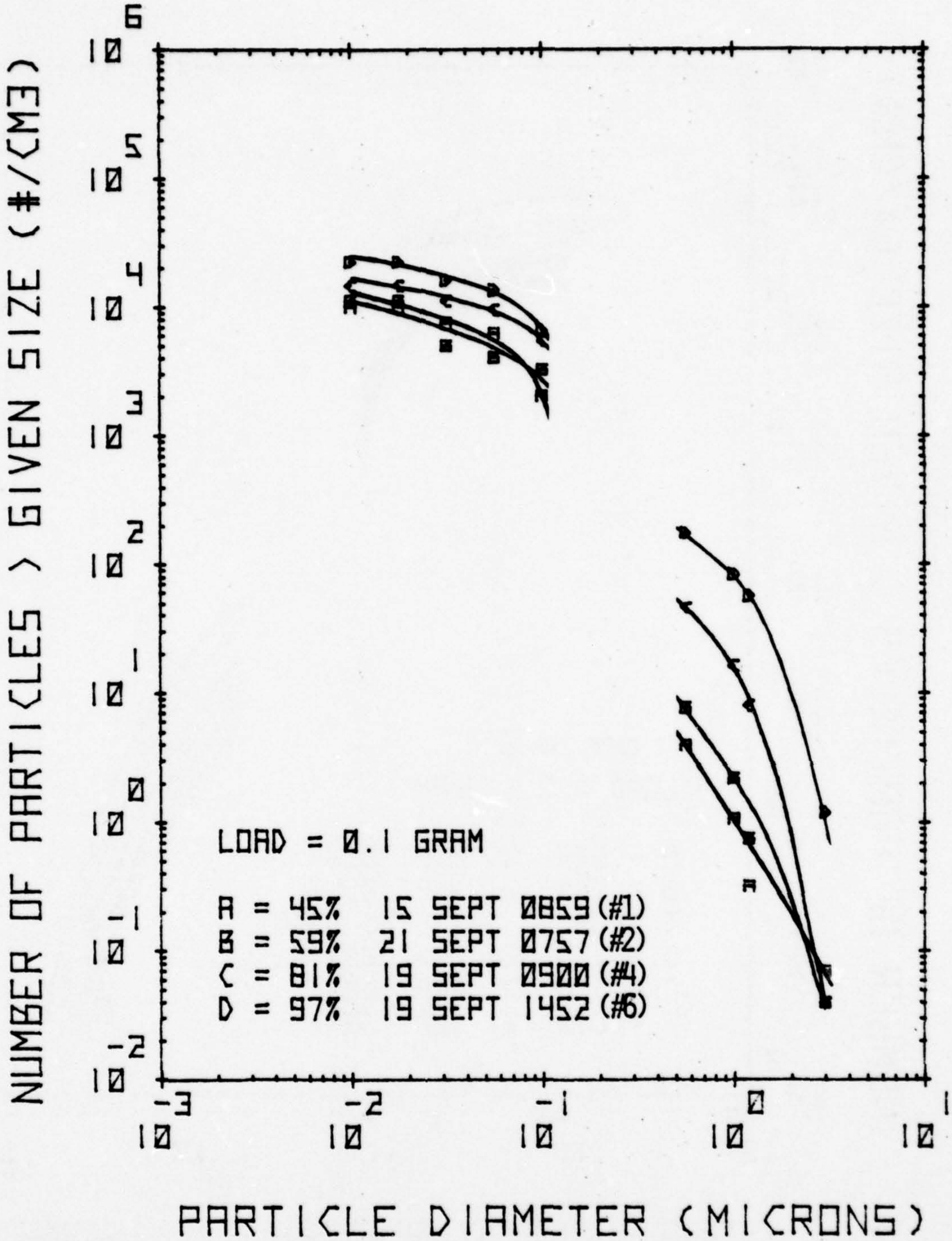


Figure 13: Aerosol Size Spectra for Four Relative Humidities in Four 0.1 g Experiments

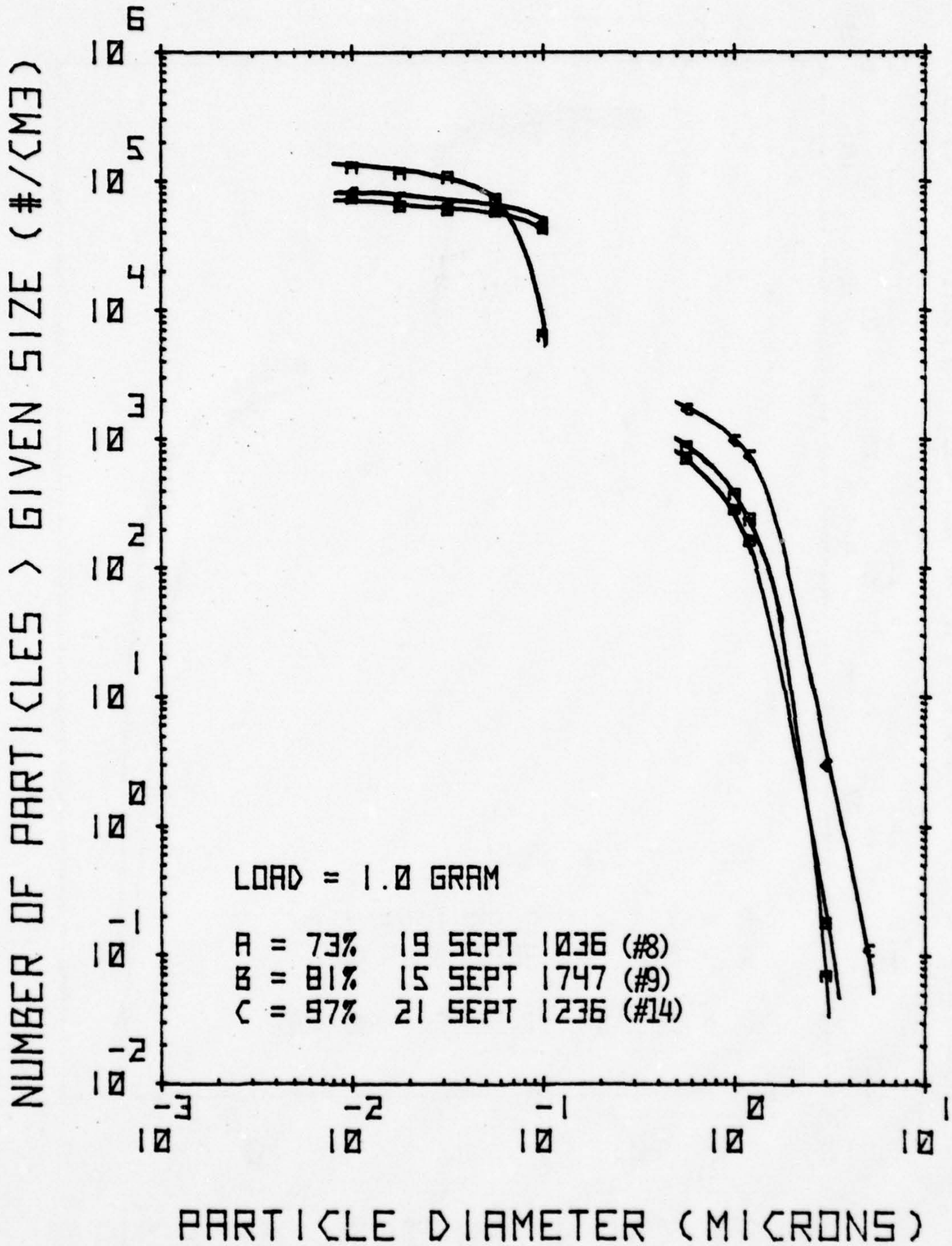


Figure 14: Aerosol Size Spectra for Three Relative Humidities in Three 1.0 g Experiments

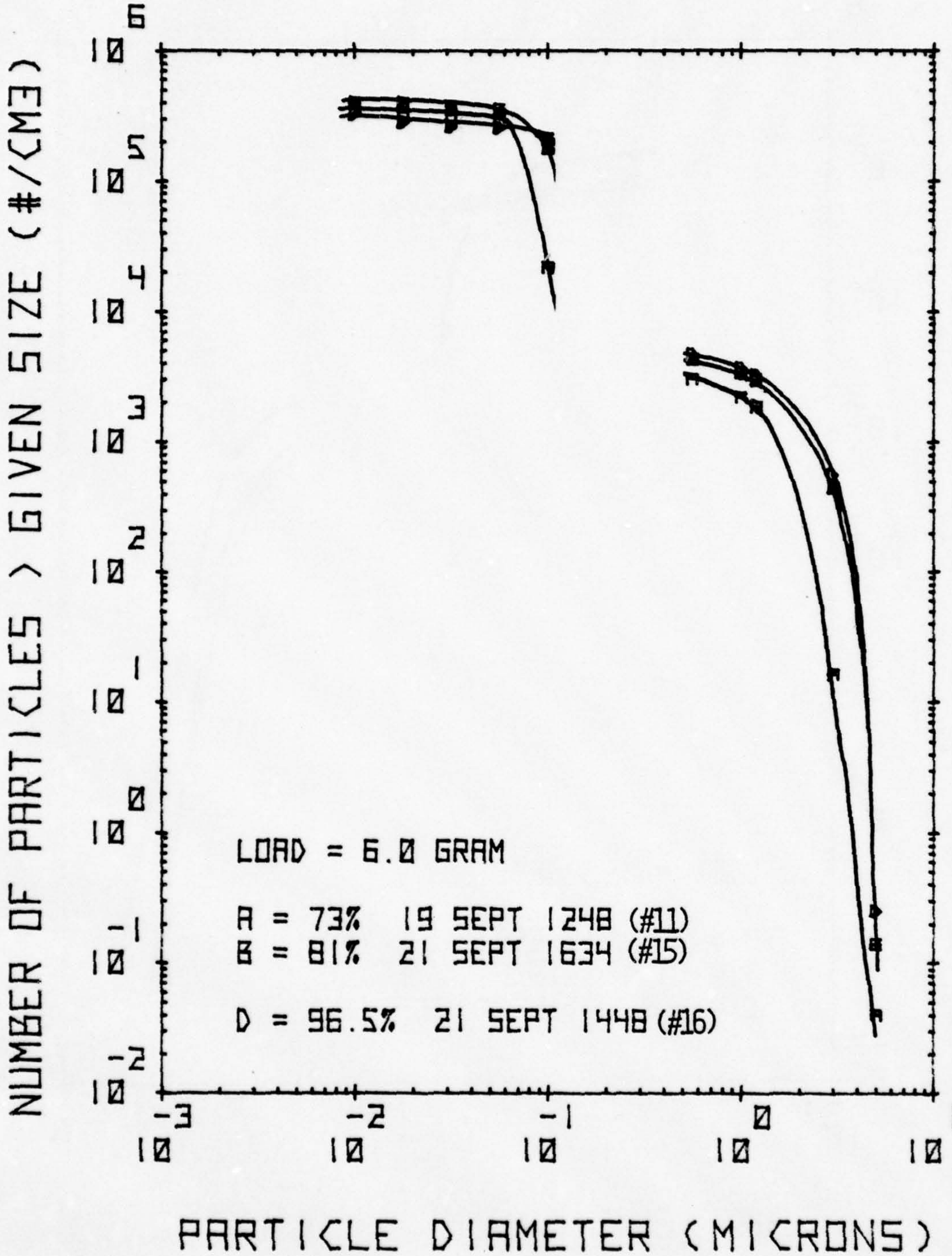


Figure 15: Aerosol Size Spectra for Three Relative Humidities in Three 6.0 g Experiments

The growth in the spectra for 1 g payloads (Figure 14) from 80 to 97% RH was similar to that of the 0.1 g experiments shown in Figure 13. However, aerosol growth in the 6 g experiments appears to have been somewhat retarded. It is not known for certain whether the apparent reduction in growth is attributable to vapor depletion effects or to coincidence problems with the Royco particle counter at these high particle concentrations; the latter cause is suspected.

For completeness, aerosol spectra for different Salty Dog payloads are compared at relative humidities of 81% and 95-97% in Figures 16 and 17, respectively. The data show, as expected, substantial differences in the respective aerosol spectra, arising primarily as a result of the differing quantities of pyrotechnic burned in the experiments.

The stability of the Salty Dog pyrotechnic aerosol fogs may be quantified in terms of visibility improvement resulting from a reduction in relative humidity. A visibility improvement factor may be computed from the ratio of the visibility measured at the lower relative humidity to that measured before relative humidity reduction was initiated. Visibility improvement factors (visible wavelength only) from applicable experiments (including two preliminary experiments) conducted during the investigation are presented in Table 4. Visibility improvement factors were computed for a 5% RH reduction and the for maximum RH reduction achieved in each experiment. As shown in the table, visibility improvement factors were typically 1.2-1.4 for a 5% drop in relative humidity, indicating that visibilities improved only by $<50\%$ for a 5% RH reduction. In several experiments, typically the higher humidity experiments, improvement factors of $\sim$2.3 were observed for 5% RH reductions. However, the maximum observed improvement factor, even for RH reductions of $\sim$10%, was only $\sim$2.5, indicating that visibility only slightly more than doubled as a result of 10% RH reductions in those experiments.

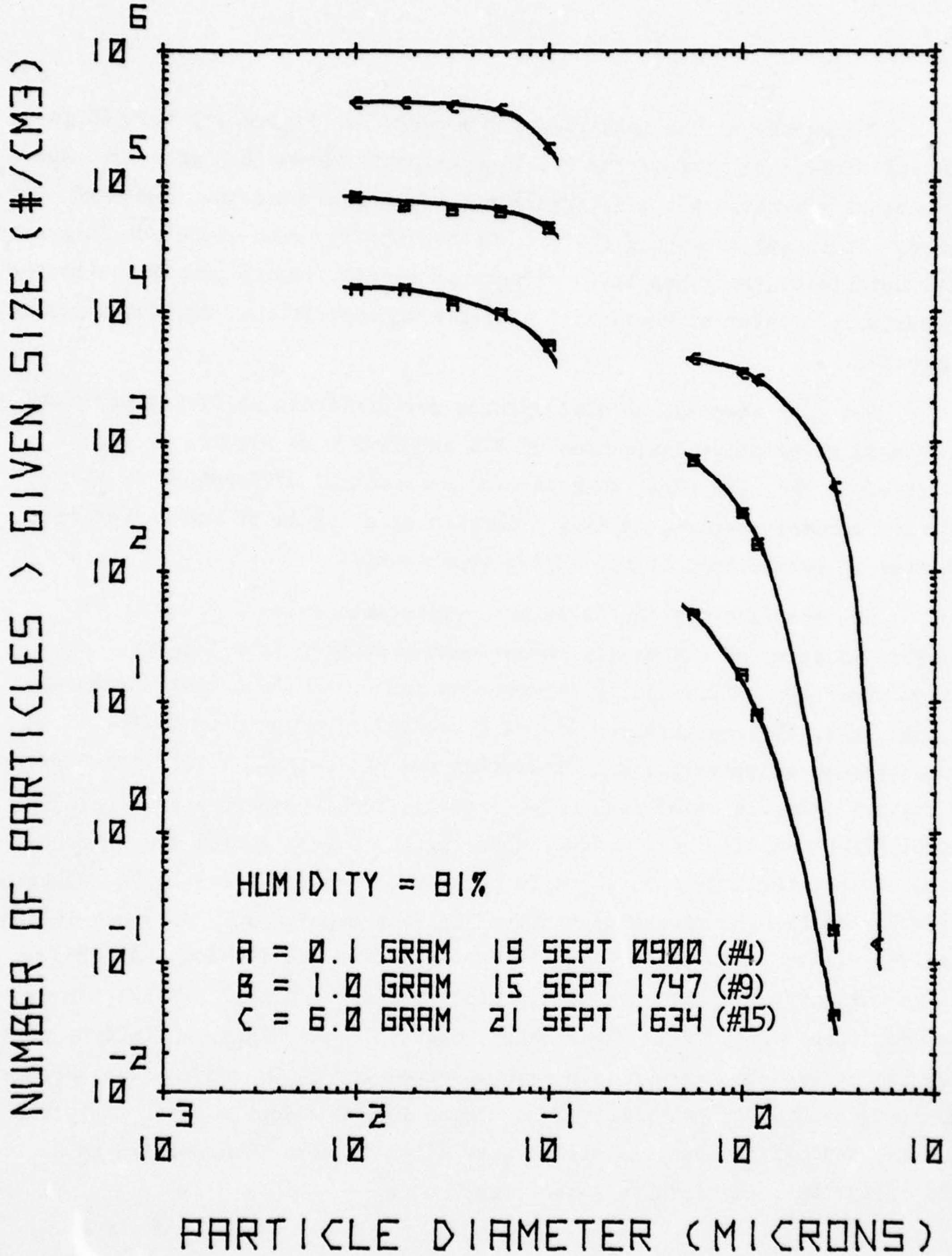


Figure 16: Aerosol Size Spectra for Three Different Salty Dog Payloads in Three Experiments at 81% Relative Humidity

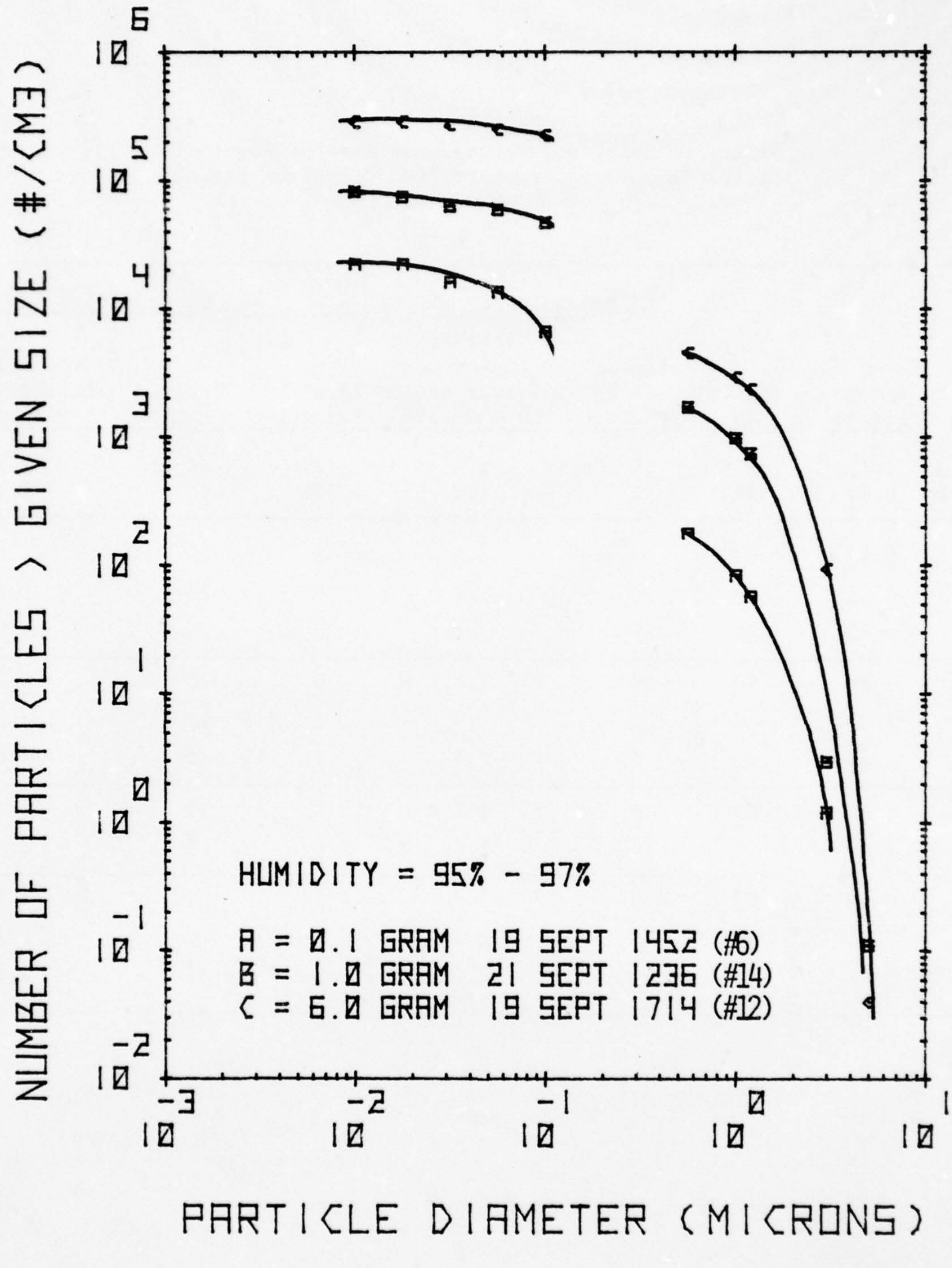


Figure 17: Aerosol Size Spectra for Three Different Salty Dog Payloads in Three Experiments at 95-97% Humidity

Table 4

Stability of Salty Dog Pyrotechnic Aerosol Fogs:
Visibility Improvement Factors Resulting From Forced
Lowering of Relative Humidity

	Expt. No.	Amount Burned	Initial RH	RH Reduction of 5%: Time To 5% RH Reduction	RH Reduction of 5%: Visibility Improvement Factor at 5% RH Reduction	Max RH Reduction: Total RH Reduction	Max RH Reduction: Time Required	Max RH Reduction: Visibility Improvement Factor
Prelim. Expts.	A	1.11g	95%	18 min	1.5	14%	80 min	2.1
	B	0.20	85%	21	1.2	10%	50	1.4
	4	0.10	81	17	1.2	6	22	1.2
	5	0.11	80	15	1.1	6	20	1.2
	6	0.09	97	15	1.4	8	25	1.5
	8	1.06	79	20	1.1	5	20	1.1
	9	1.05	82	-	-	2	14	1.6
	10	1.04	96	30	2.4	7	50	2.6
	11	5.96	79	20	1.2	6	23	1.2
	12	5.97	96	10	1.4	9	20	1.7
Cetyl Alch. Experiments	14	0.94	97	22	2.3	5	22	2.3
	15	6.08	82	25	1.3	6	30	1.4
	16	6.07	96.5	30	2.2	5	30	2.2

Note that the improvement factors for the cetyl alcohol "stabilized" fogs (Experiments 14, 15 and 16) were greater on the average than those of the untreated fogs. However, the differences in visibility improvement factors between the untreated and cetyl alcohol-treated fogs were probably within experimental scatter, suggesting that cetyl alcohol had no effect on the stability of the Salty Dog aerosol fogs. It is not known to what extent the aerosols were coated with cetyl alcohol, but the untreated fogs may be sufficiently stable as to eliminate the need for stabilizers.

Section 4
CONCLUSIONS AND RECOMMENDATIONS

The following principal conclusions have been derived from this limited laboratory investigation of Salty Dog pyrotechnics:

1. Yield from the pyrotechnic in terms of aerosols of >0.01 μm diameter was $\sim 10^{13}$/gram, of which ~30% were greater than 0.1 μm in size;

2. The output of particles >1.0 μm diameter was found to be relative humidity dependent, with $\sim 10^{10}$ particles being produced at RH < 70% and $\sim 5 \times 10^{11}$ being produced at 95-97% RH; relatively few particles >5 μm diameter were observed;

3. Likewise the composite extinction (visible wavelengths) for Salty Dog aerosol fogs was found to be RH dependent, average values/gram being 1.7, 7.3 and 28.0 km^{-1} for RH of < 70, 79-81 and 95-97%, respectively;

4. Extinction due to Salty Dog aerosol fogs at wavelengths longer than the visible was only a fraction of that observed at visible wavelengths; at 2.15 μm wavelength, extinction was only 10-20% of that for visible; at ~7.7-9.8 μm wavelength, extinction was only 2-4% of that for visible wavelengths; in contrast extinction in natural fogs (with droplets of 5-20 μm diameter) was found to be comparable at visible and far IR wavelengths;

5. The pyrotechnic aerosol fogs were found to be extremely stable; visibility improvement factors of 2 were typical for relative humidity reductions of 10%; hence, evaporation retardants (stabilizers) are probably not necessary;

6. Cetyl alcohol was found to be ineffective in reducing visibility improvement factors--for the conditions of our experiments.

The results of these experiments have shown that the Salty Dog aerosol fog can be an extremely dense screen at visible wavelengths and particularly at higher relative humidities, exhibiting good stability for relative humidity changes of the order of 10%. However, extinction at longer wavelengths is particle size and refractive index dependent. To be a more effective screen at longer wavelengths, measures will have to be taken to increase the particle size of the Salty Dog aerosols; e.g., coagulation, altering of burn rate and temperature, altering the chemical composition, etc. Additives or primary material with specific absorption characteristics in the IR might also improve extinction characteristics at longer wavelengths. It is recommended that attempts to alter particle size and absorption characteristics be undertaken.

Finally, if the observed stability of the Salty Dog aerosol fogs is not sufficient for Navy needs, it is recommended that experimentation with evaporation retardants be expanded to determine the specific utility of candidate materials.

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Kocmond, W.C., W.D. Garrett and E.J. Mack, 1972: Modification of Laboratory Fog with Organic Surface Films, J. Geop. Res., 77, 18, pp 3221-3231.

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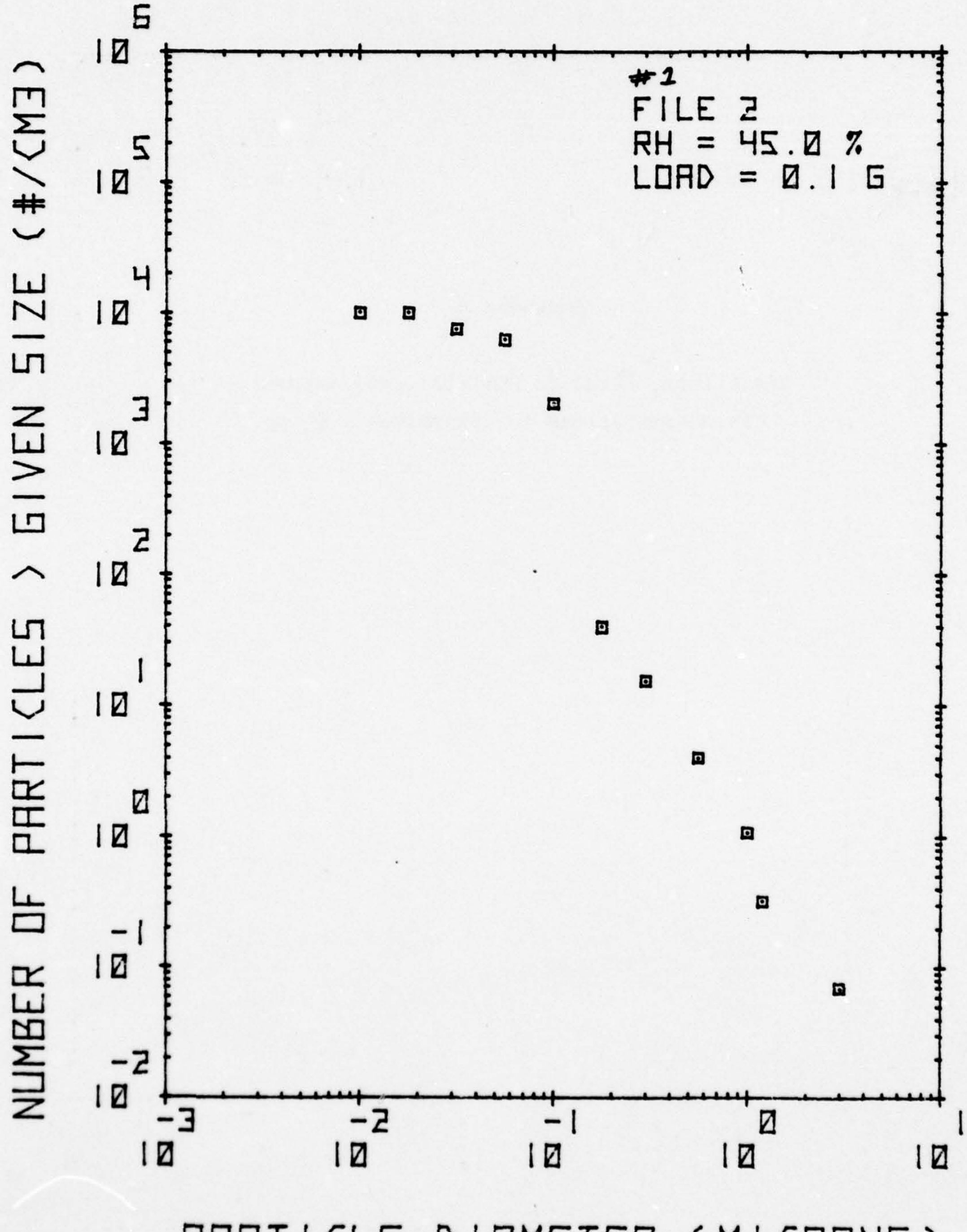
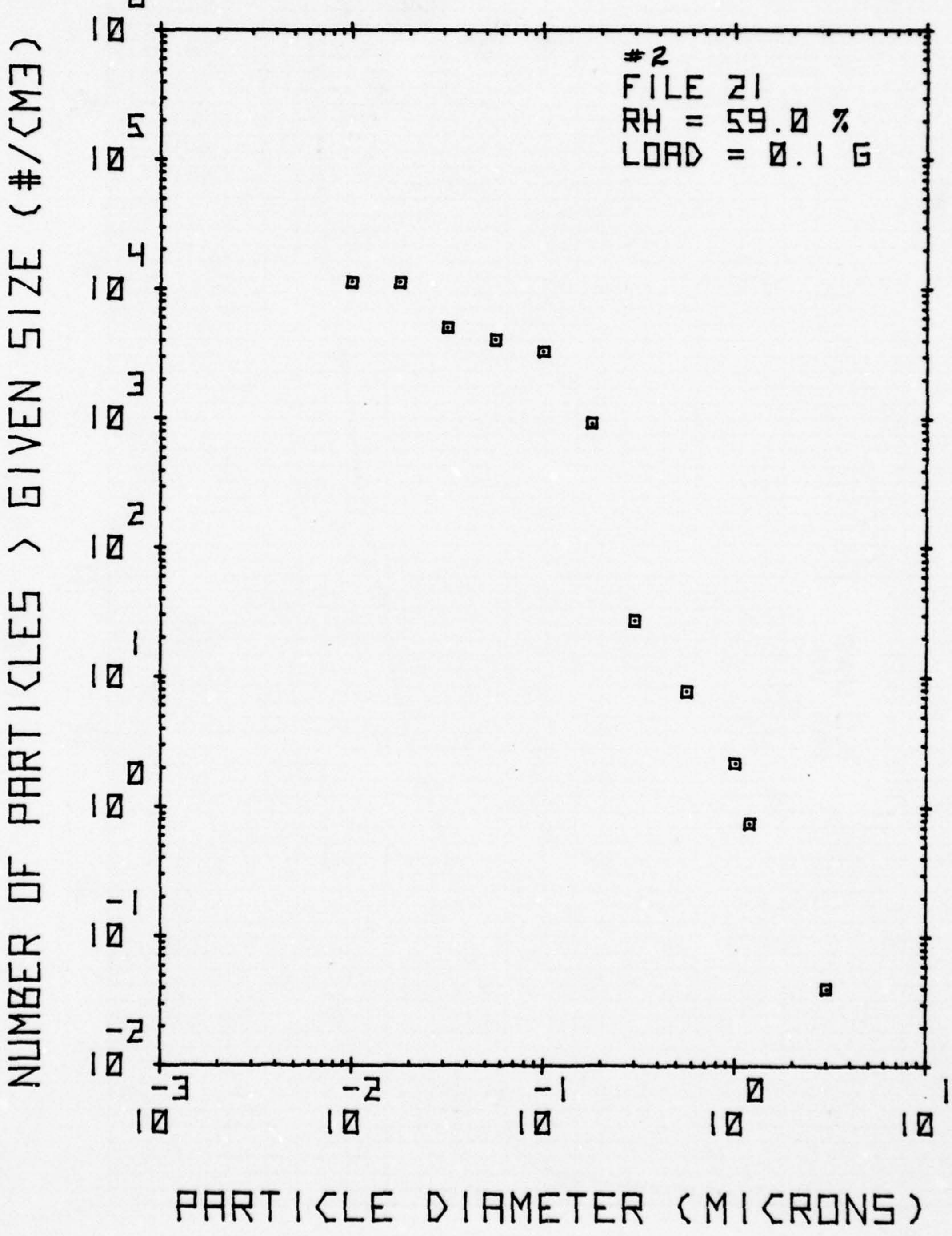
Mack, E.J., R.J. Anderson, C.K. Akers, and T.A. Niziol, 1978: "Aerosol Characteristics of the Marine Boundary Layer of the North Atlantic and Mediterranean During May-June 1977," Project SEA FOG, Sixth Annual Summary Report: Part 1, Calspan Report No. 6232-M-1, 215 pp, October.

Appendix A

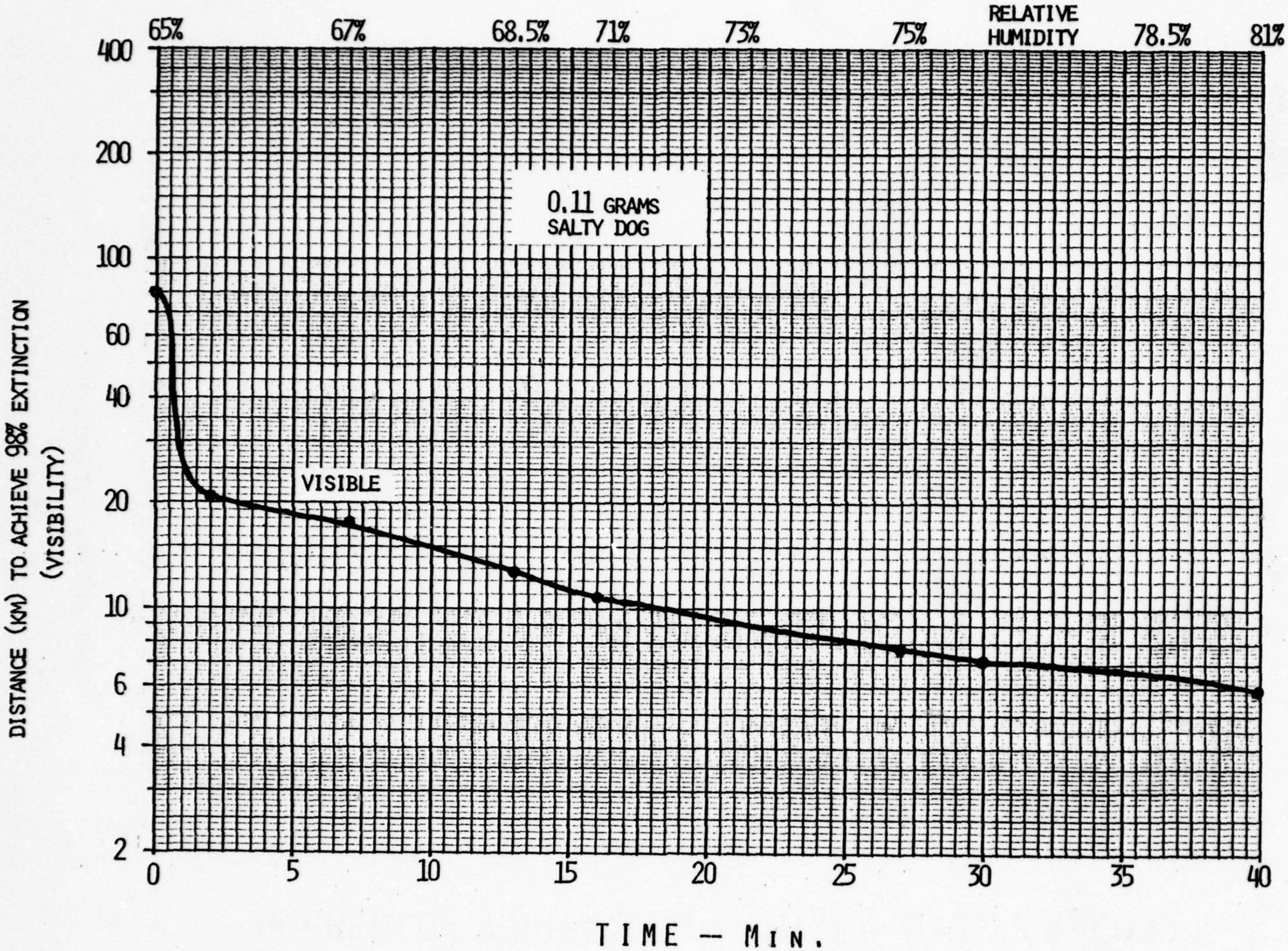
Visibility, Relative Humidity, and Aerosol Characterizations for Experiments #1-19



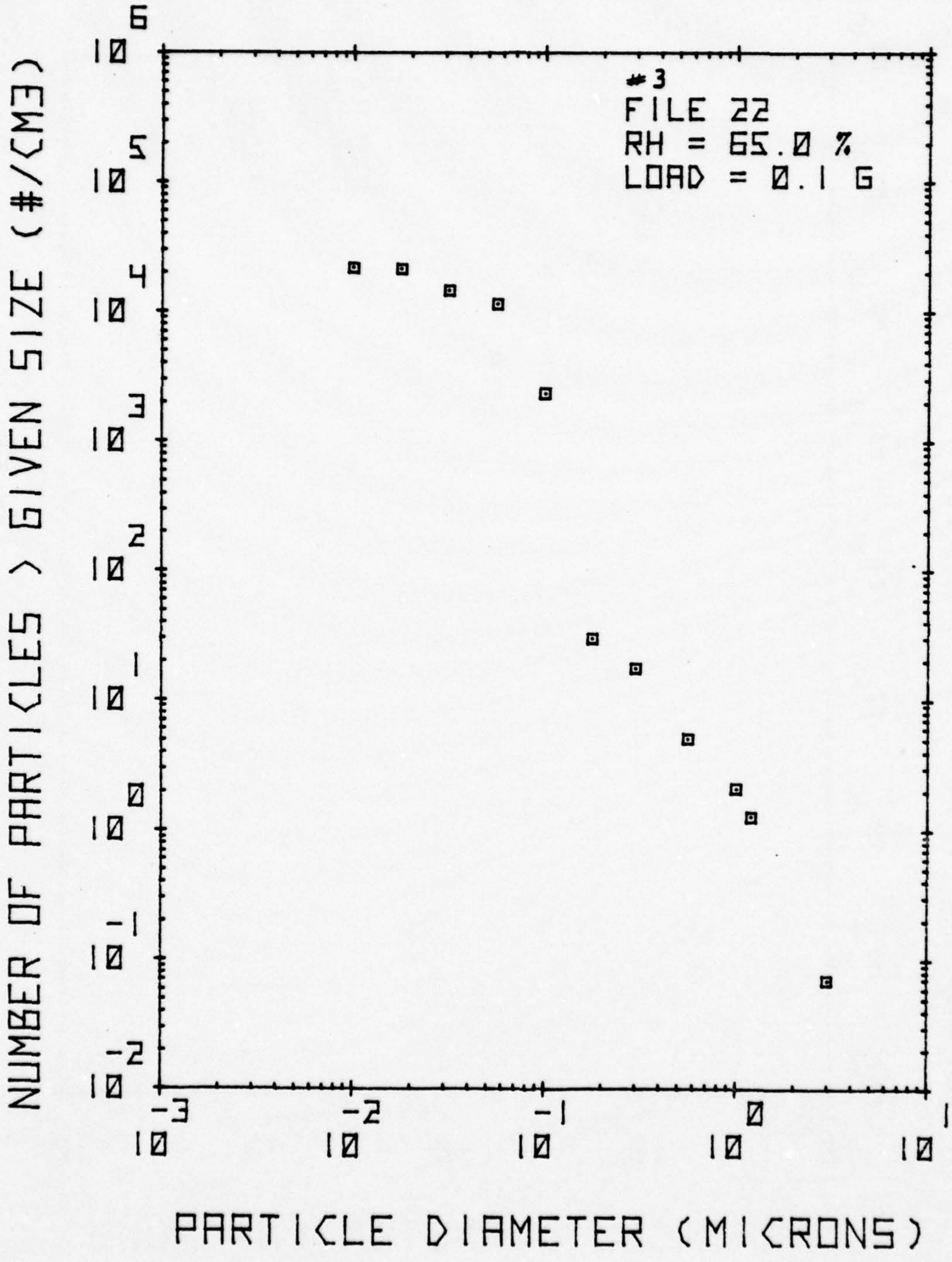
AEROSOL SPECTRUM FOR EXPERIMENT #1



AEROSOL SPECTRUM FOR EXPERIMENT #2



VISIBILITY AS A FUNCTION OF TIME IN EXPERIMENT #3



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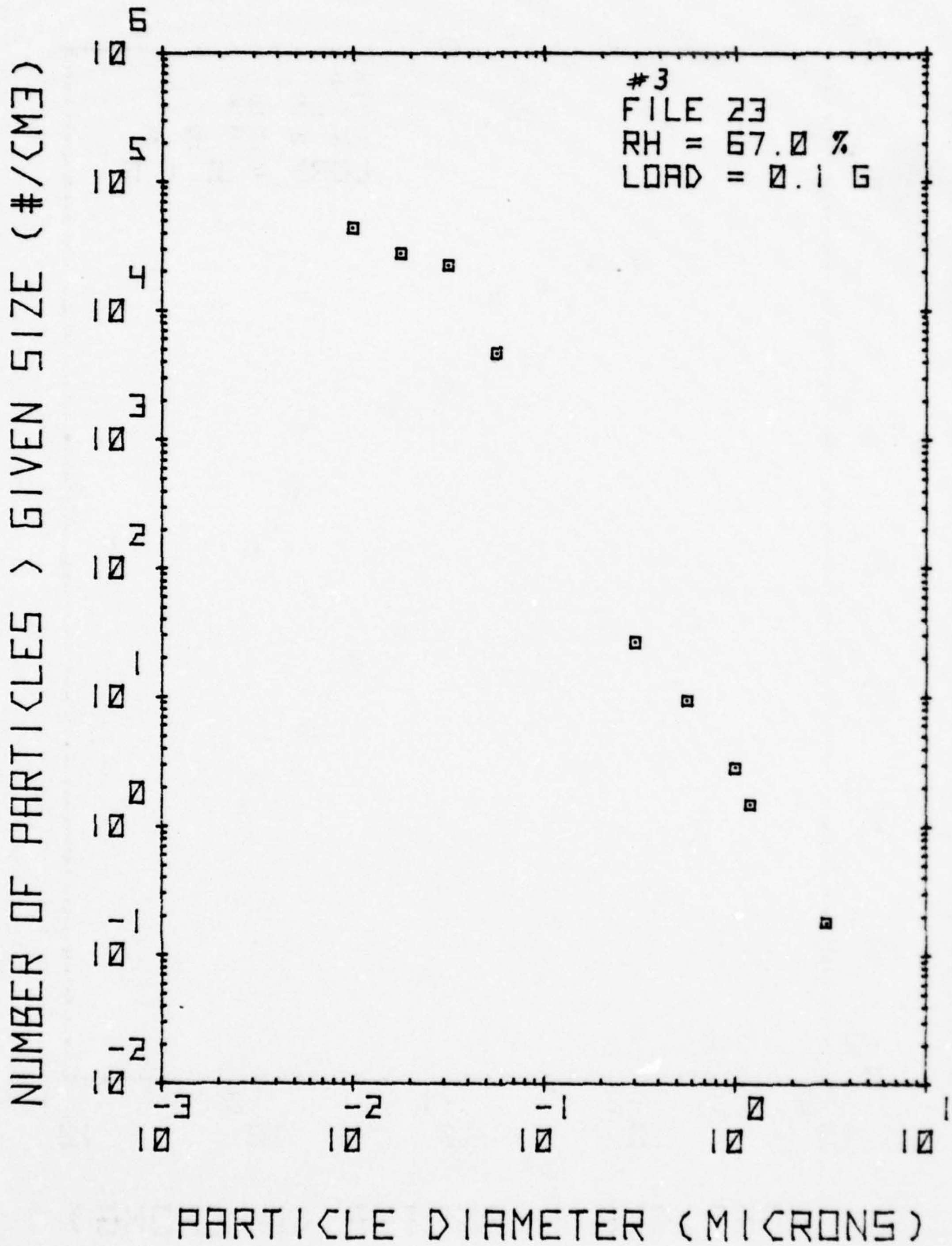
FILE 22
RH = 65.0 %
LOAD = 0.1 G
NUMBER OF PARTICLES > GIVEN SIZE (#/CM3)
PARTICLE DIAMETER (MICRONS)



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LOAD = 0.1 G
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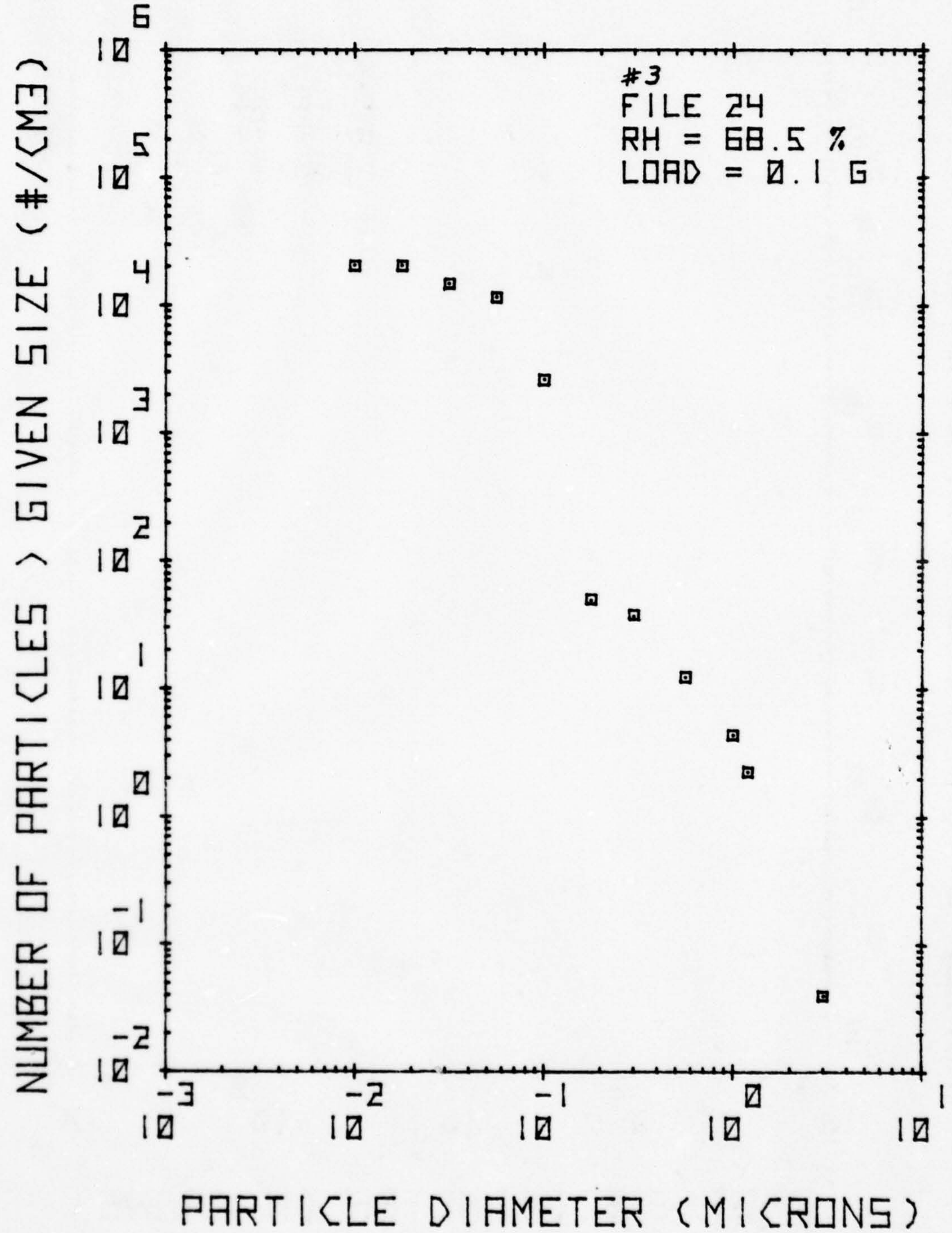
PARTICLE DIAMETER (MICRONS)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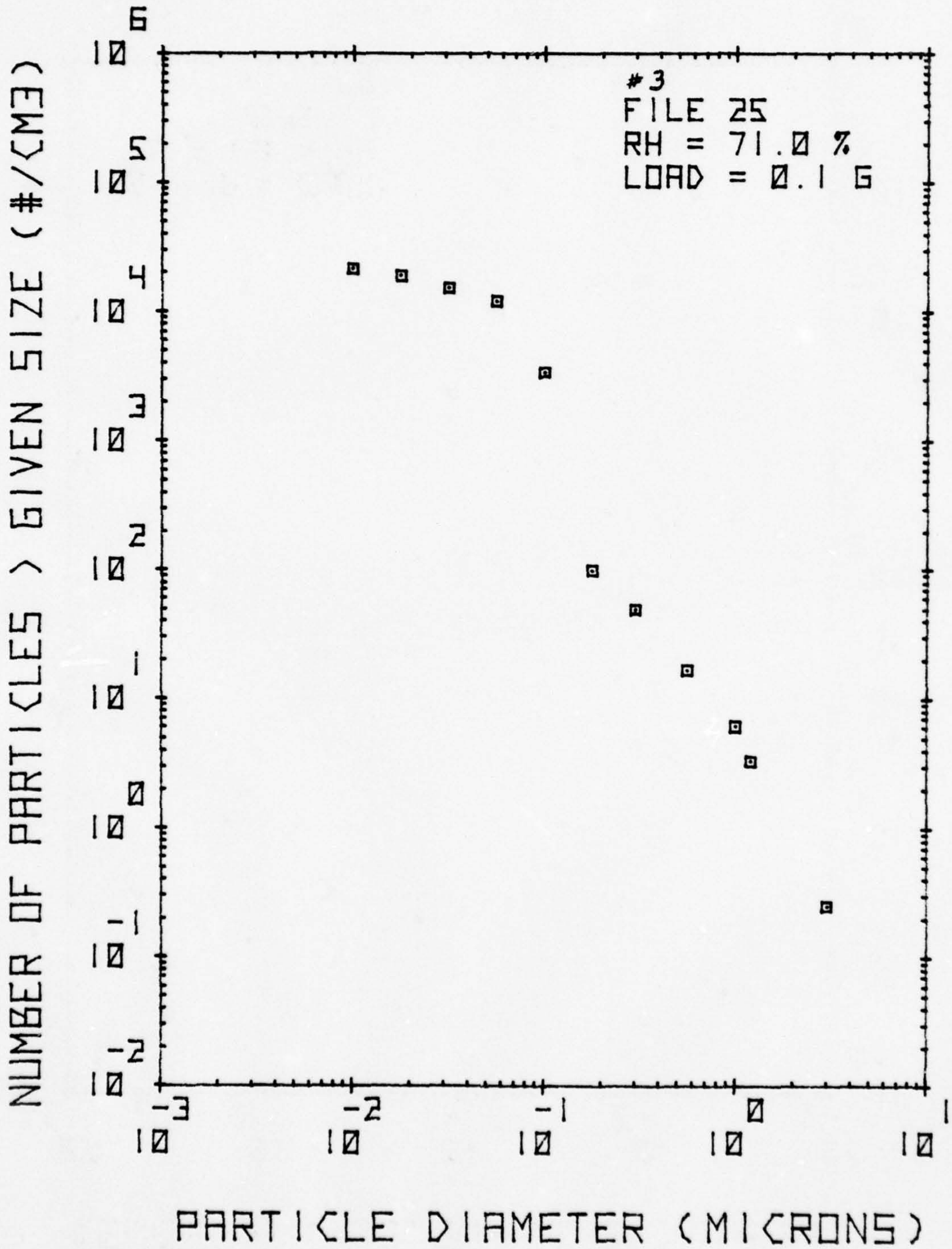
PARTICLE DIAMETER (MICRONS)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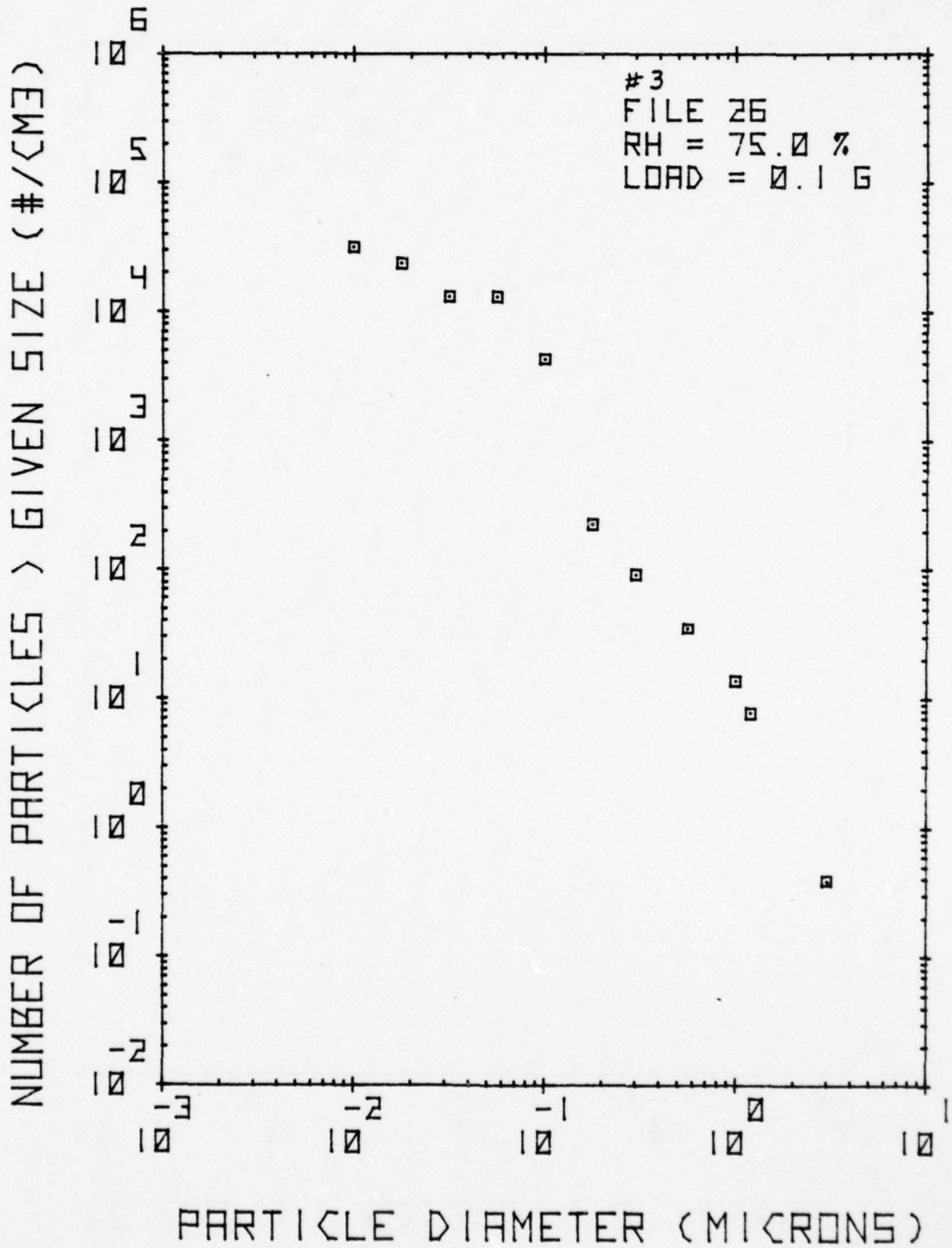
PARTICLE DIAMETER (MICRONS)



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FILE 26
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LOAD = 0.1 G
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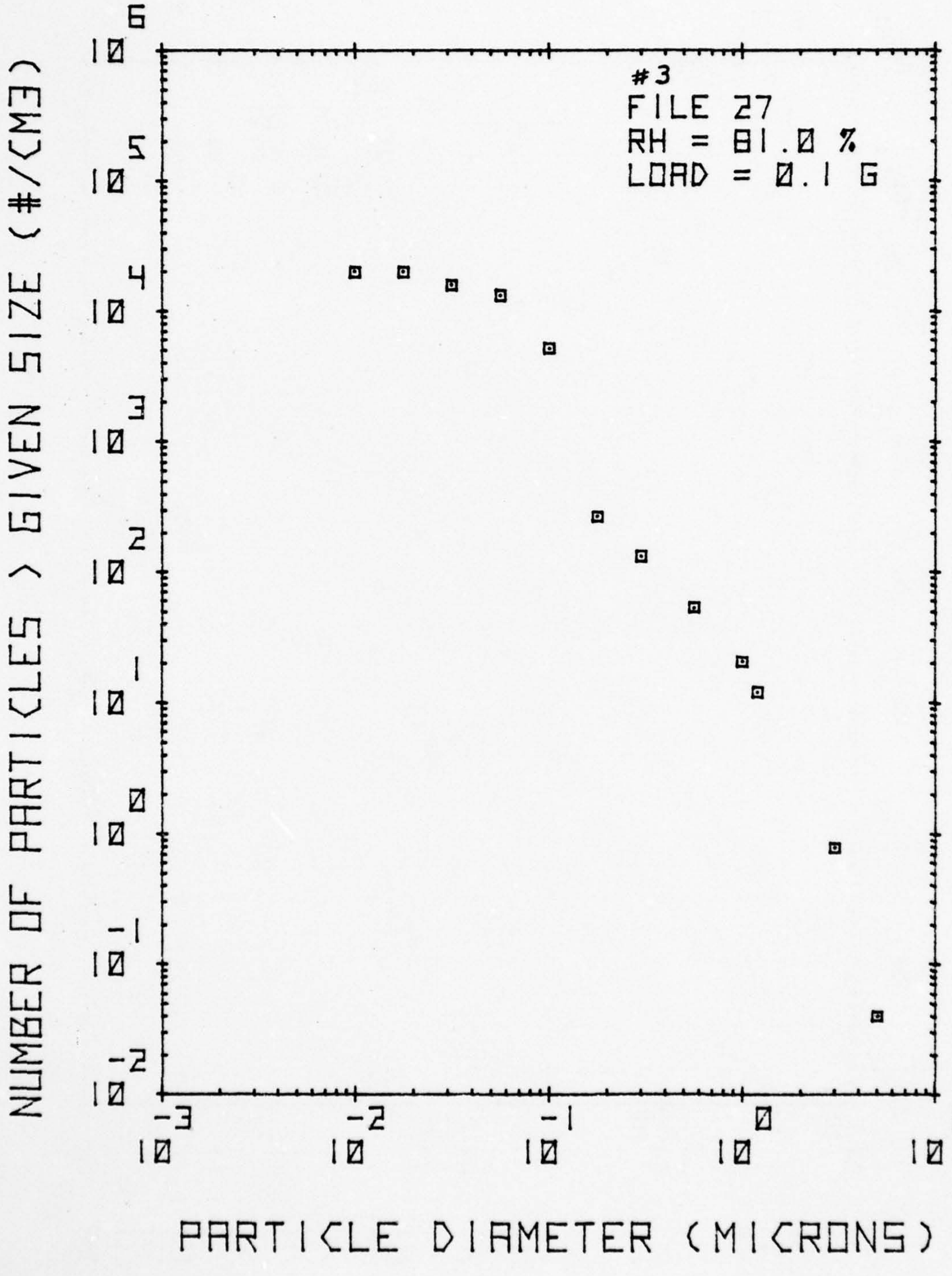
PARTICLE DIAMETER (MICRONS)
10^6
10^5
10^4
10^3
10^2
10^1
10^0
10^-1
10^-2
10^-3
10^-2
10^-1
10^0
10^1



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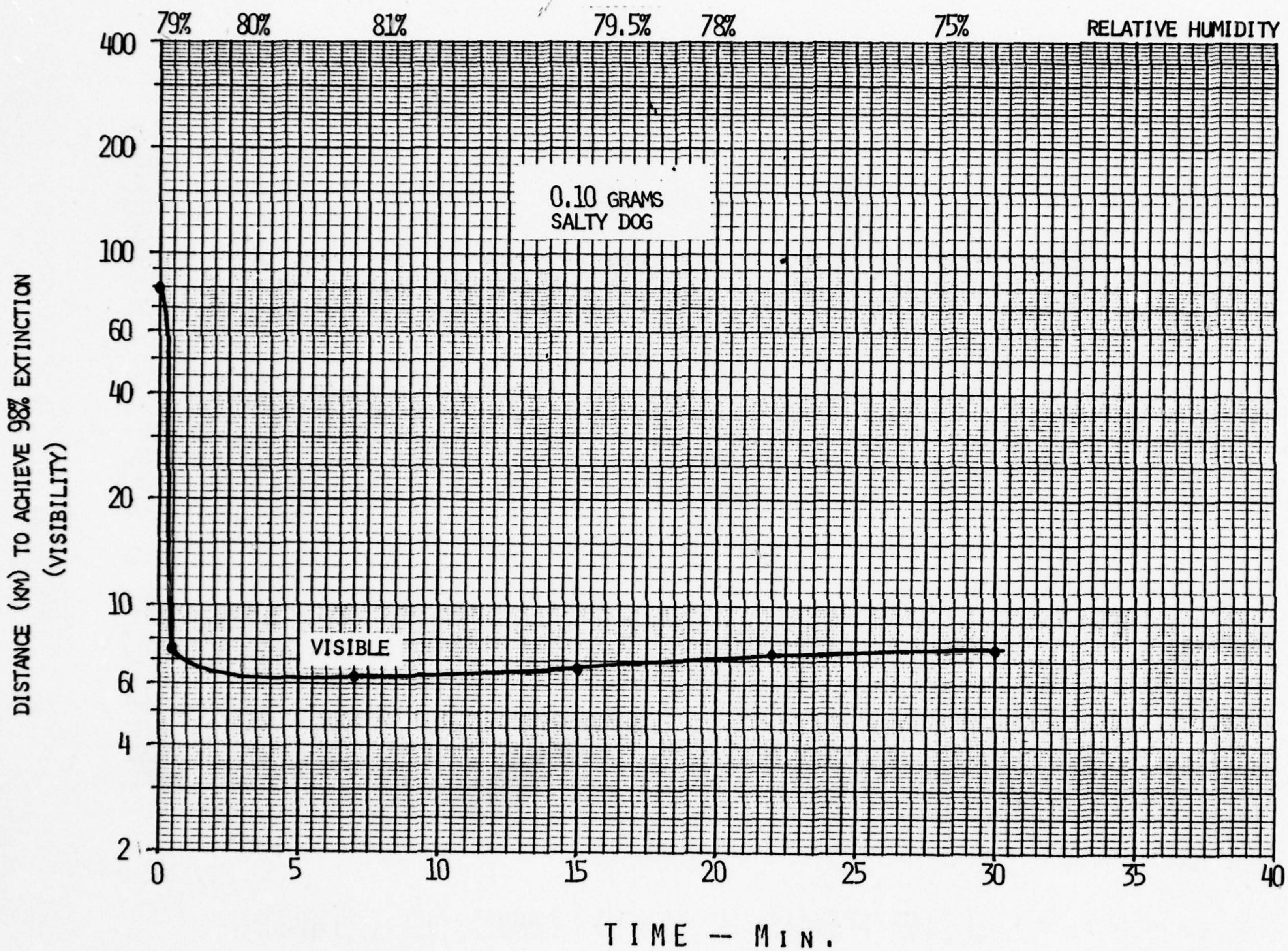
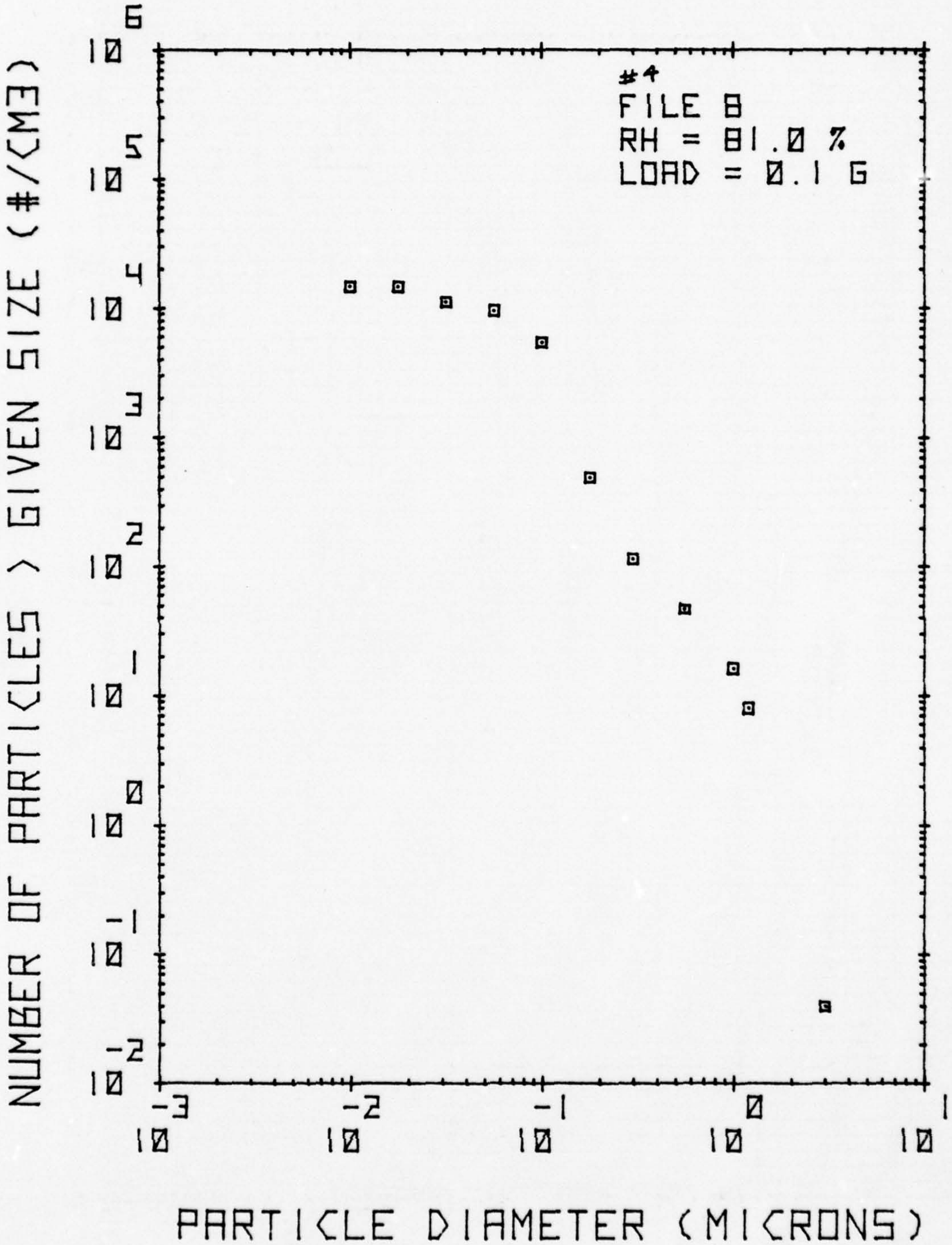
PARTICLE DIAMETER (MICRONS)



VISIBILITY AS A FUNCTION OF TIME IN EXPERIMENT #4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LOAD = 0.1 G
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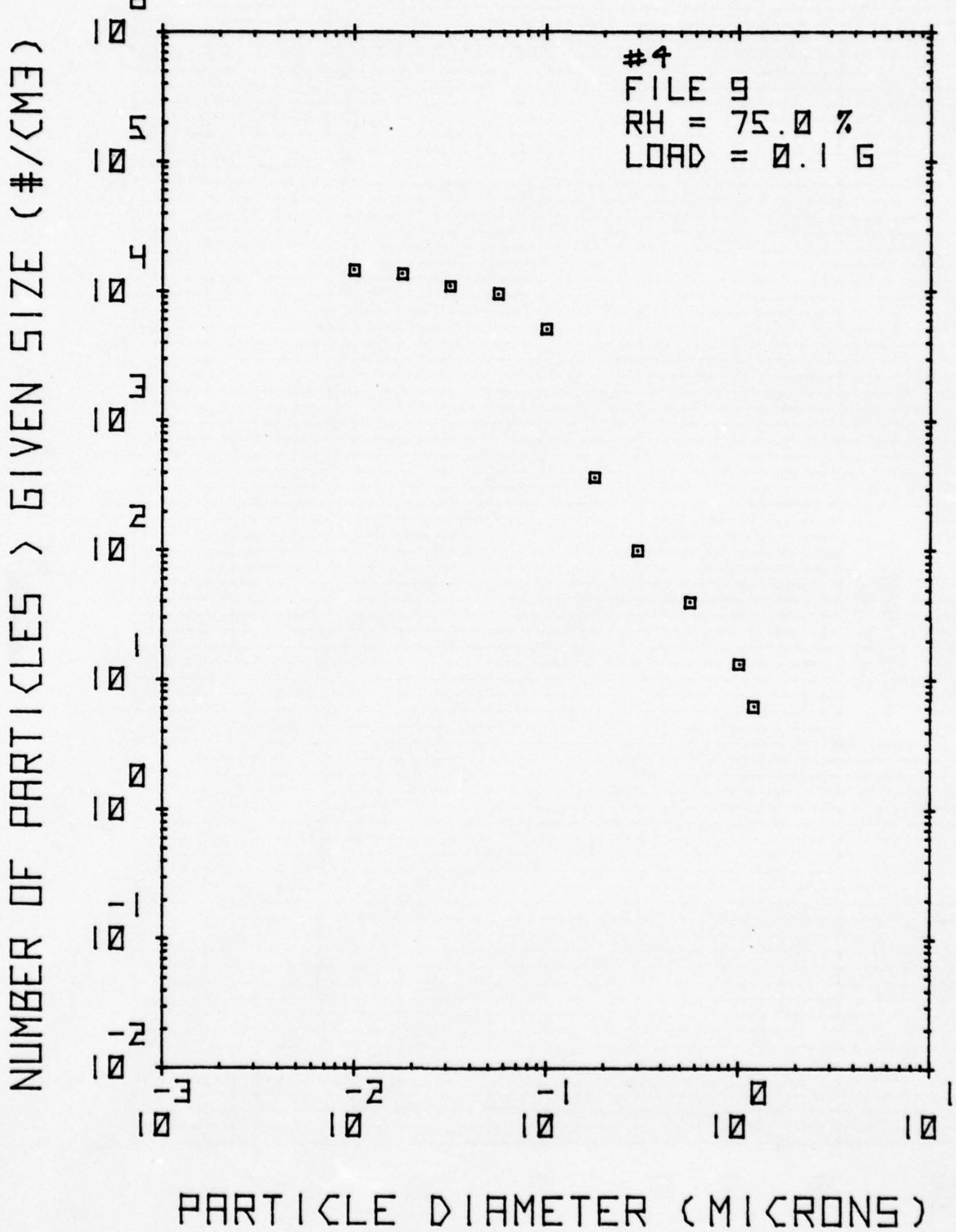
PARTICLE DIAMETER (MICRONS)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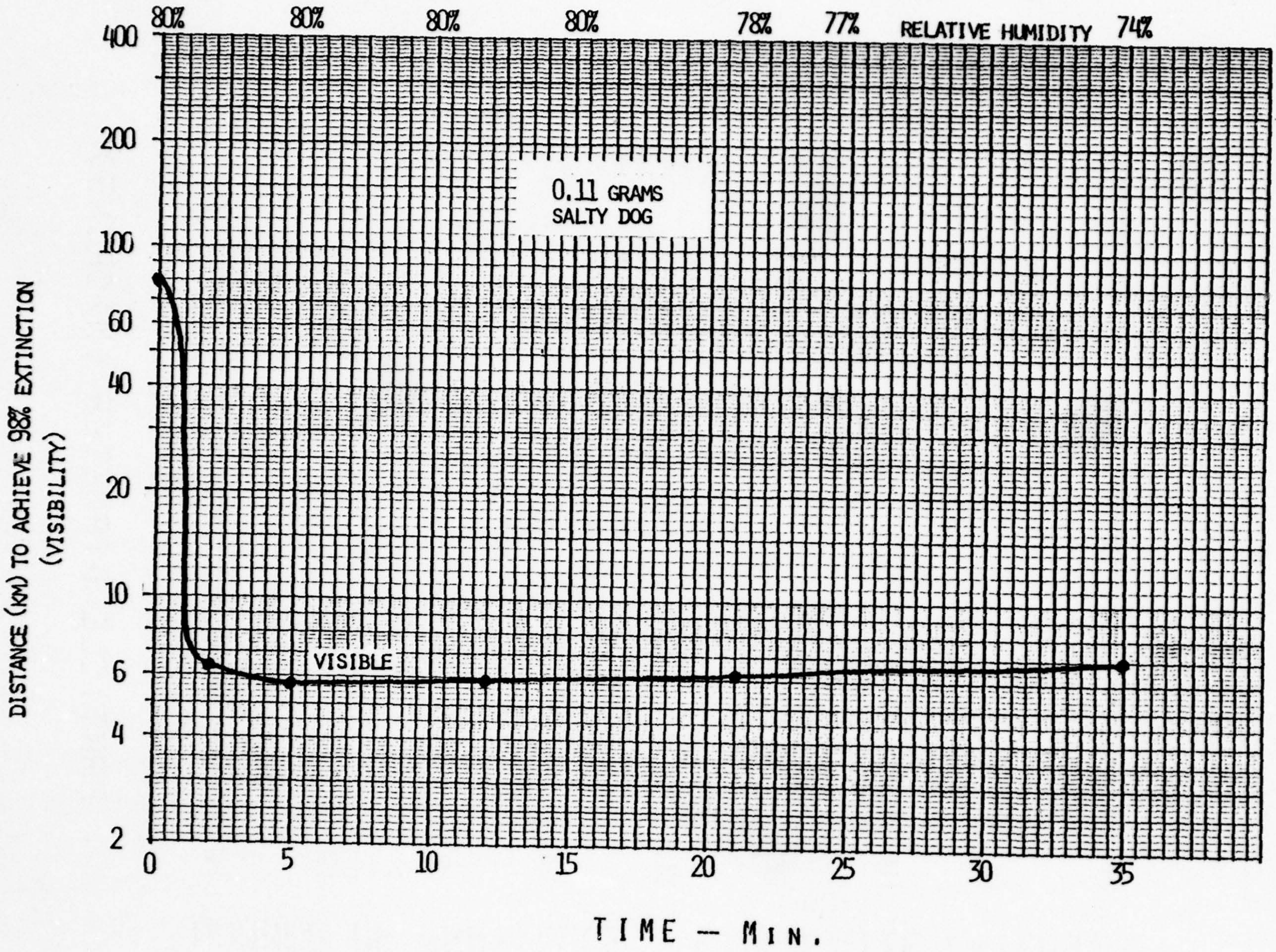
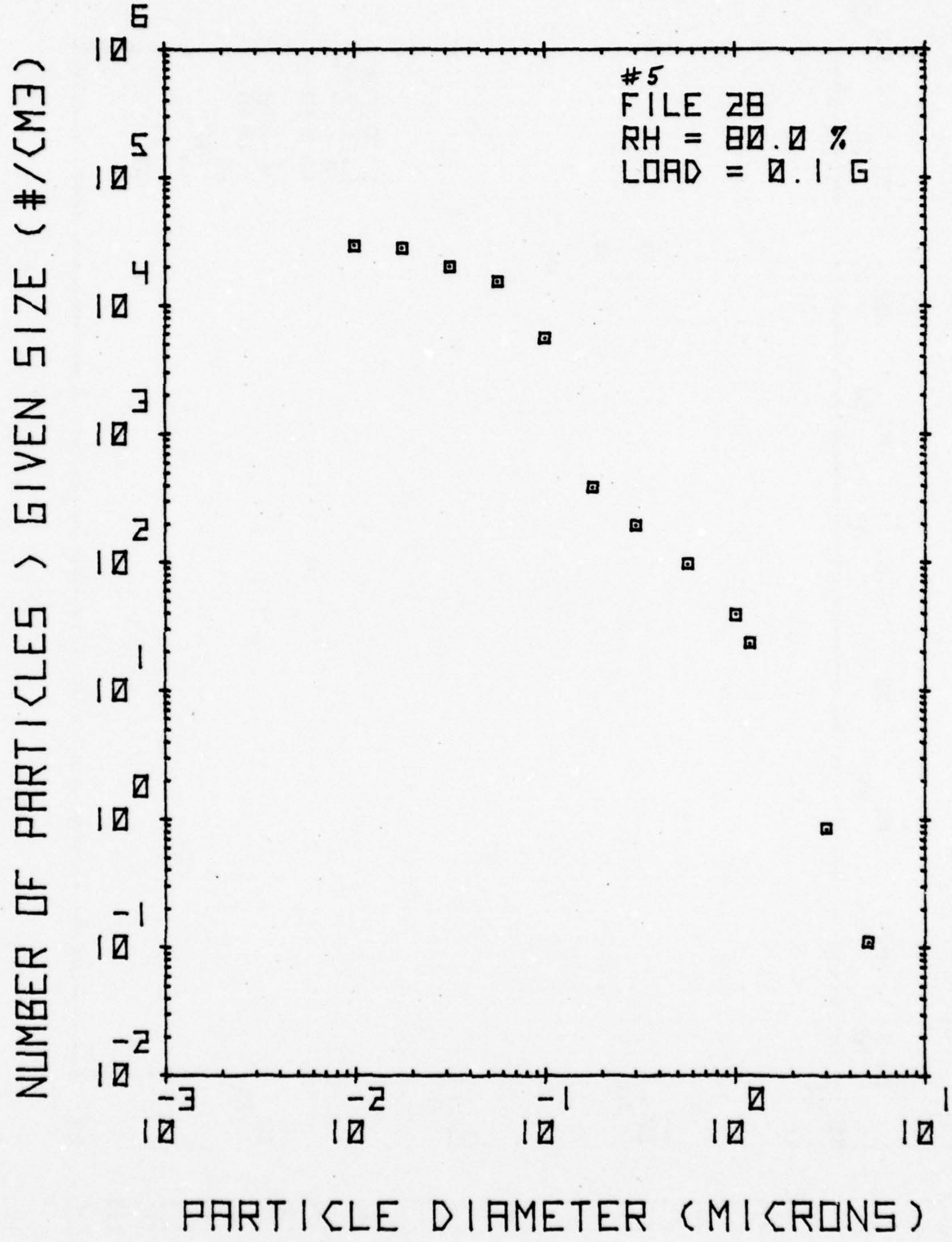


VISIBILITY AS A FUNCTION OF TIME IN EXPERIMENT #5



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LOAD = 0.1 G
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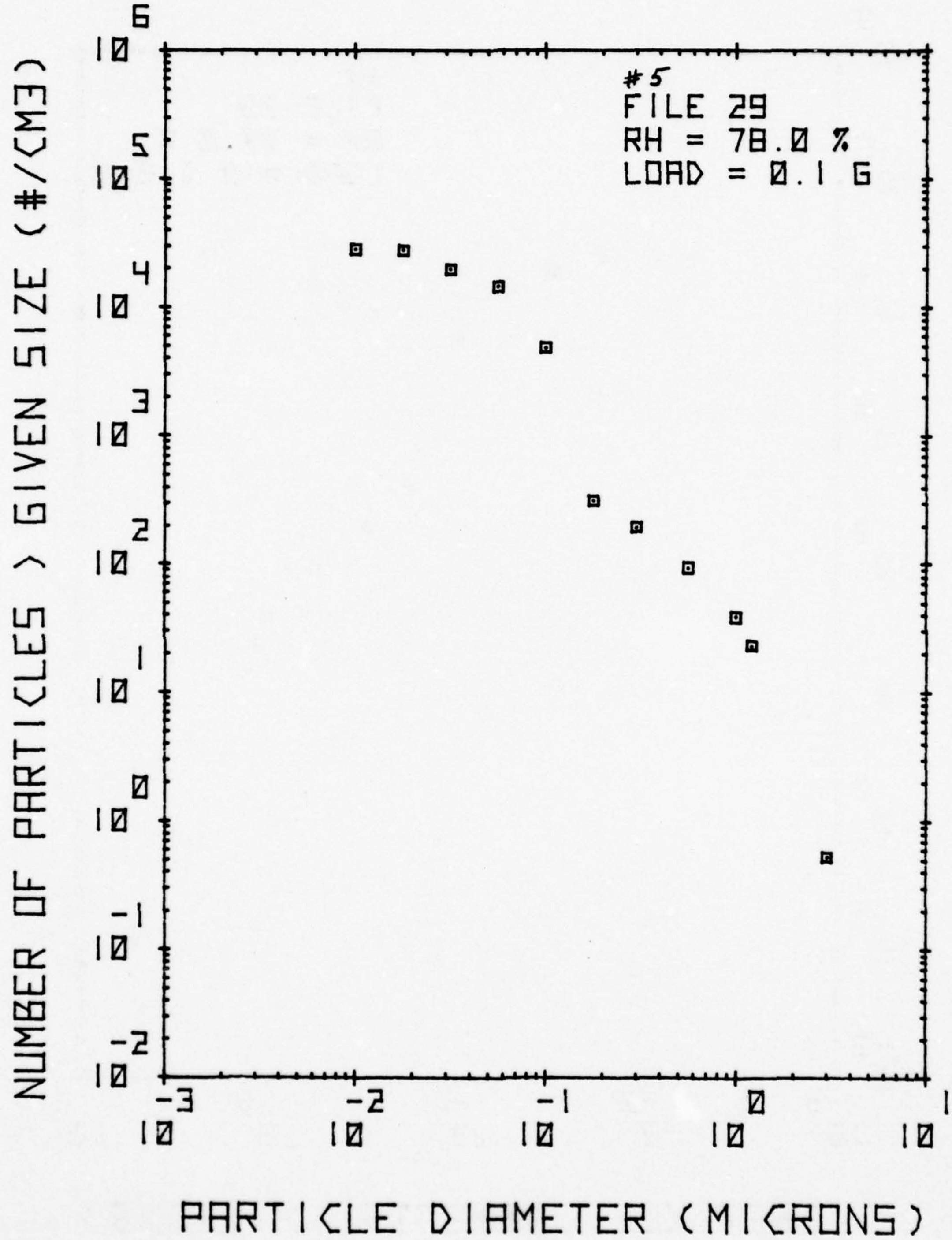
PARTICLE DIAMETER (MICRONS)



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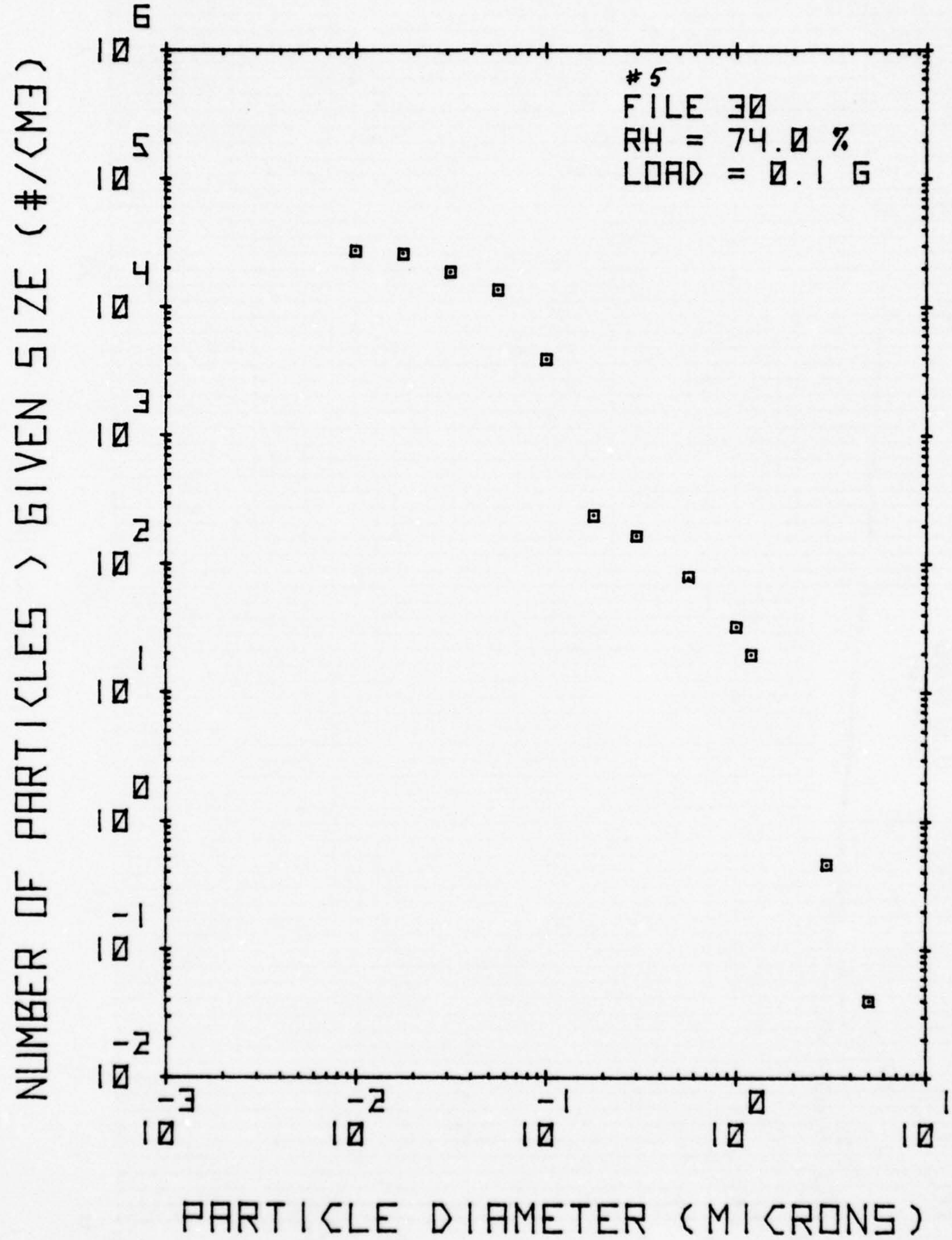
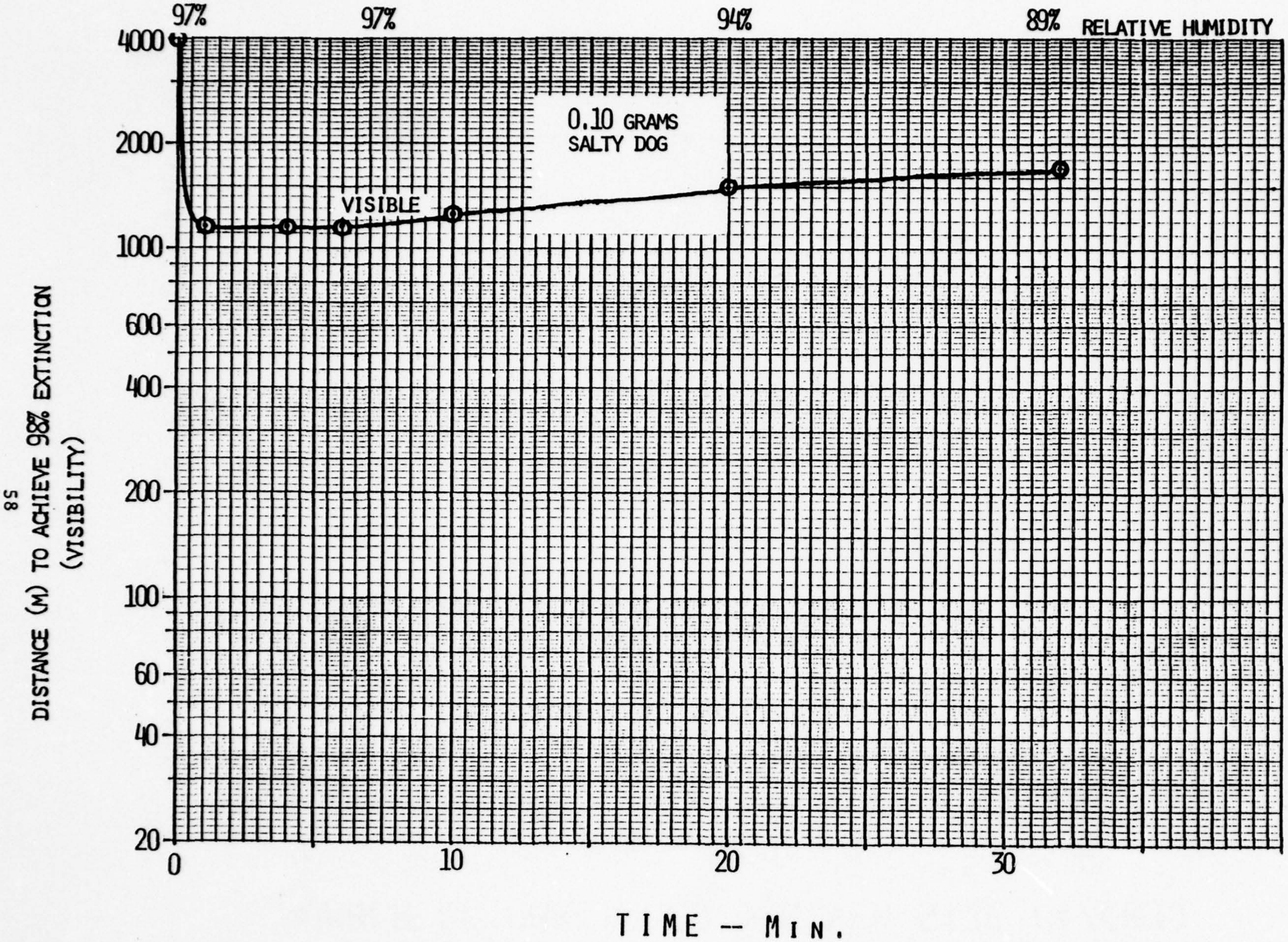
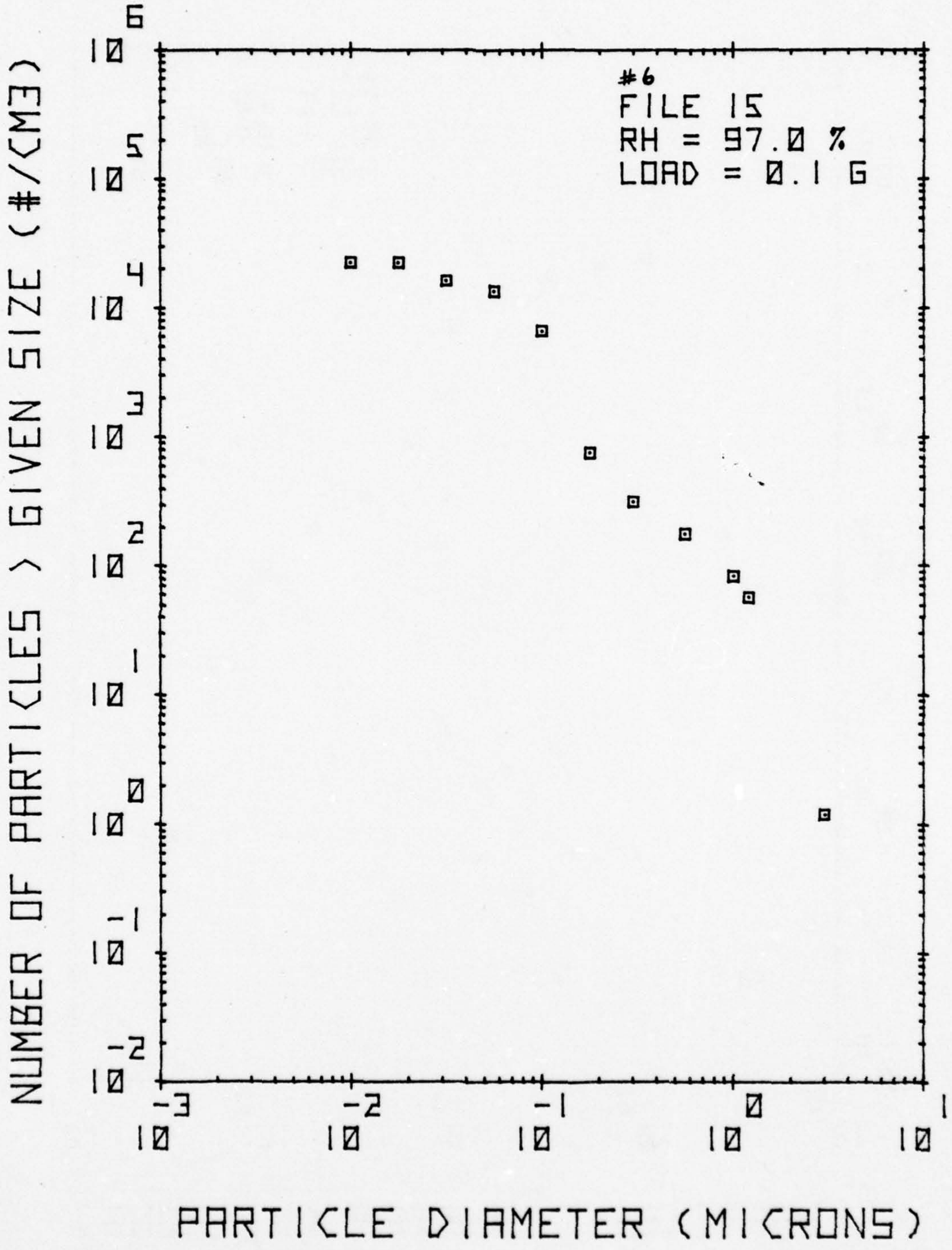
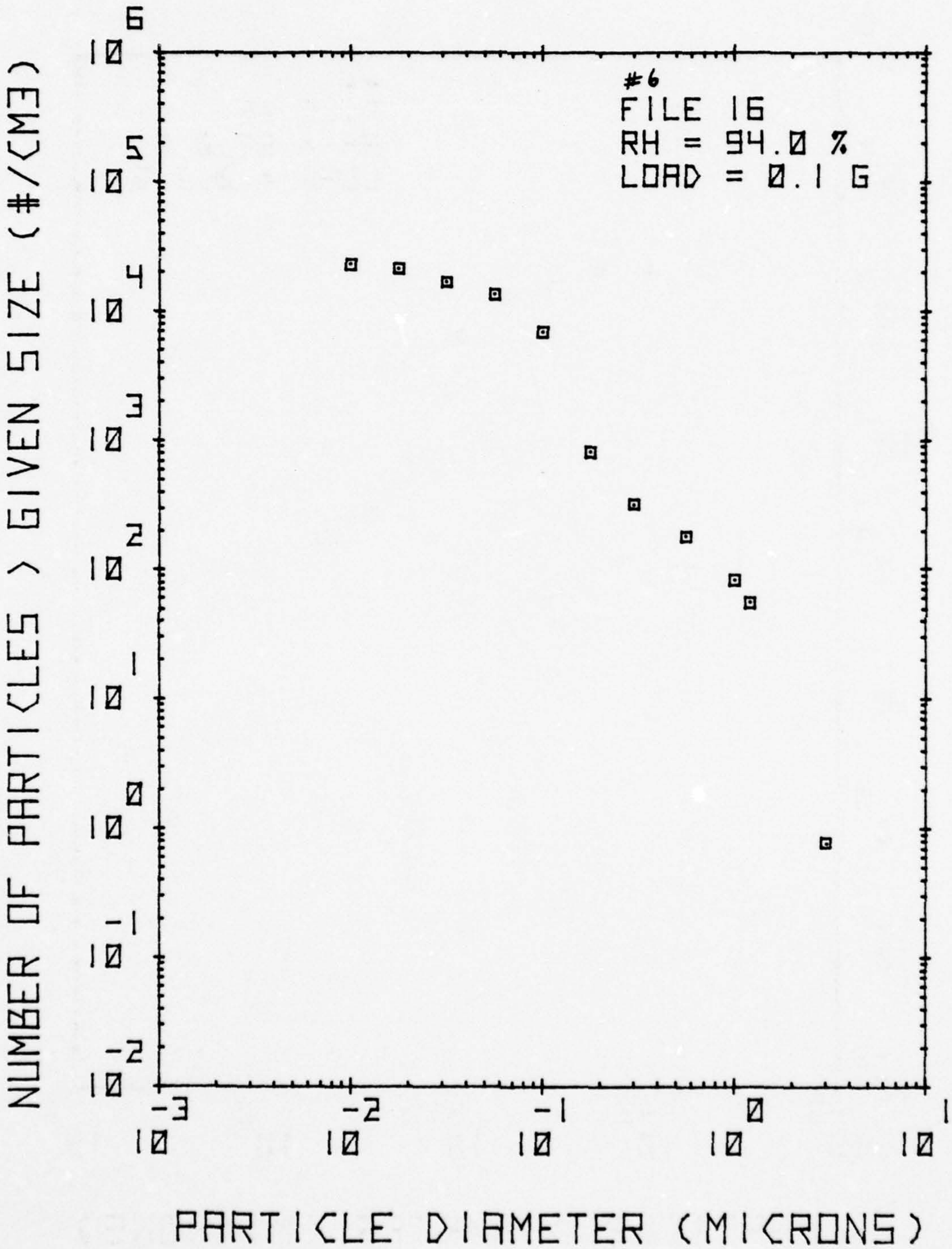
LOAD = 0.1 G
NUMBER OF PARTICLES > GIVEN SIZE (#/CM3)
PARTICLE DIAMETER (MICRONS)


#5
FILE 30
RH = 74.0 %
LOAD = 0.1 G
NUMBER OF PARTICLES > GIVEN SIZE (#/CM3)
PARTICLE DIAMETER (MICRONS)

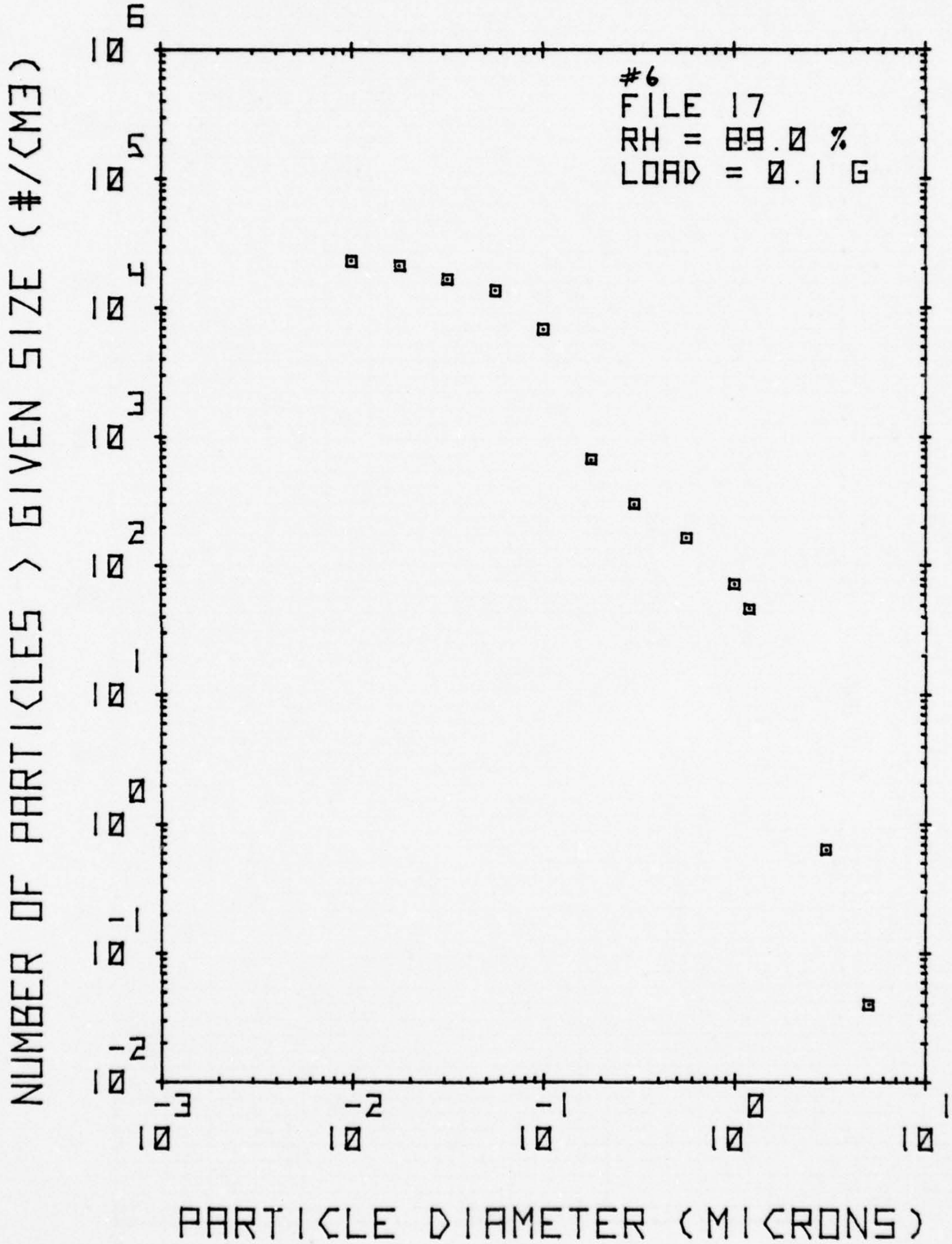


VISIBILITY AS A FUNCTION OF TIME IN EXPERIMENT #6

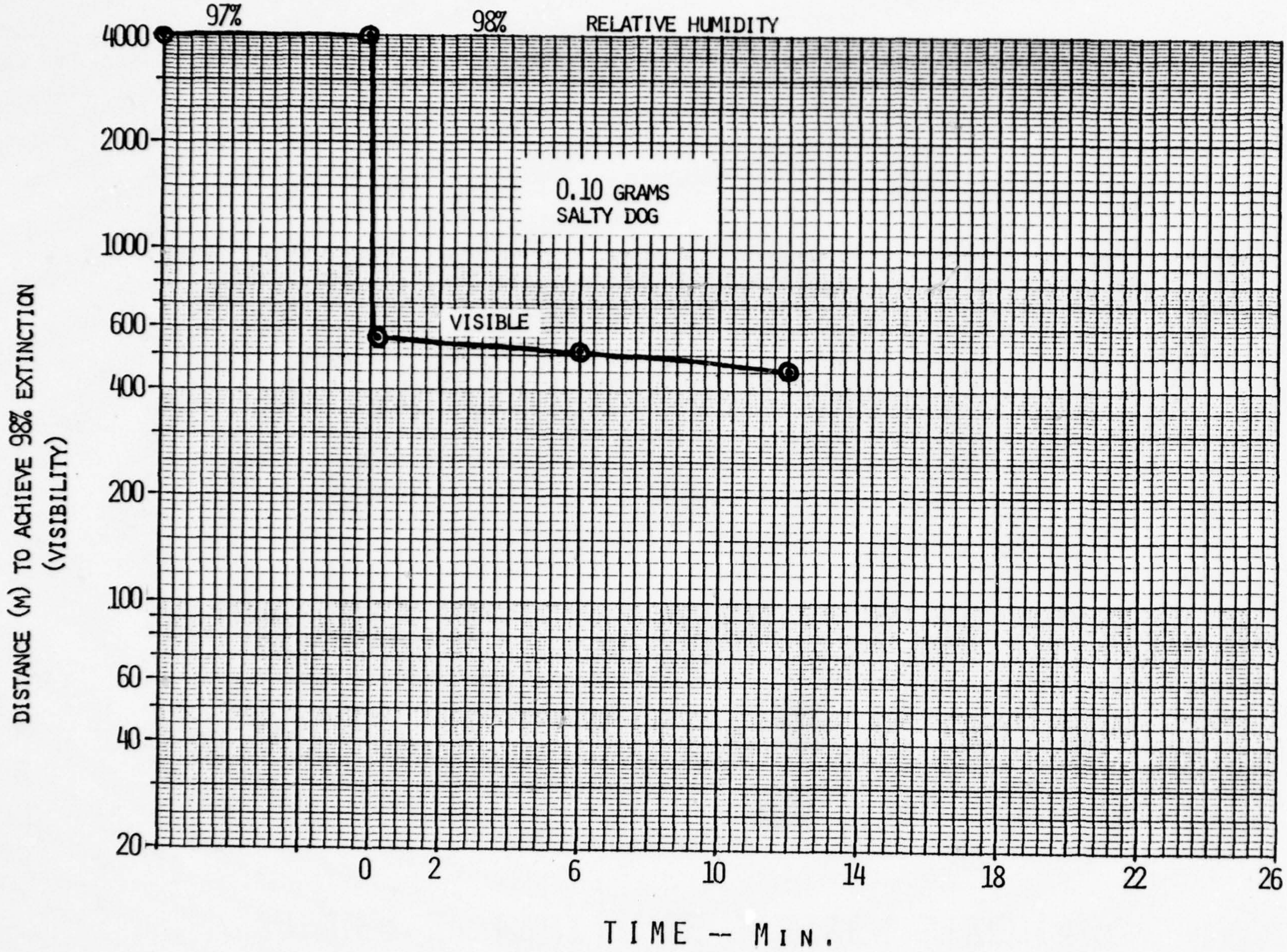

#6
FILE 15
RH = 97.0 %
LOAD = 0.1 G
NUMBER OF PARTICLES > GIVEN SIZE (#/CM3)
PARTICLE DIAMETER (MICRONS)
10^{6}
10^{5}
10^{4}
10^{3}
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}



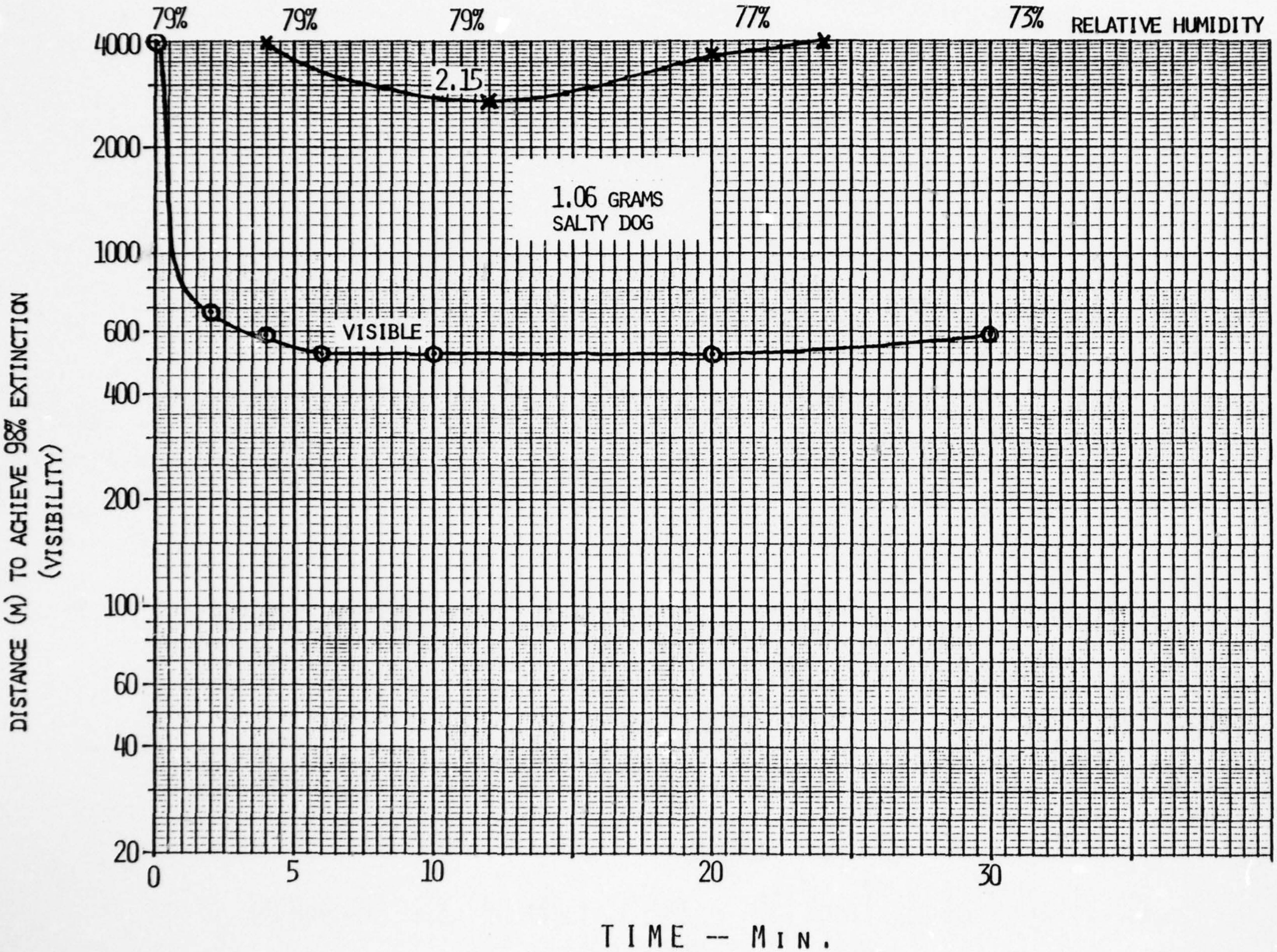
#6
FILE 16
RH = 94.0 %
LOAD = 0.1 G
NUMBER OF PARTICLES > GIVEN SIZE (#/CM3)
10^6
10^5
10^4
10^3
10^2
10^1
10^0
10^-1
10^-2
10^-3
10^-2
10^-1
10^0
10^1
PARTICLE DIAMETER (MICRONS)



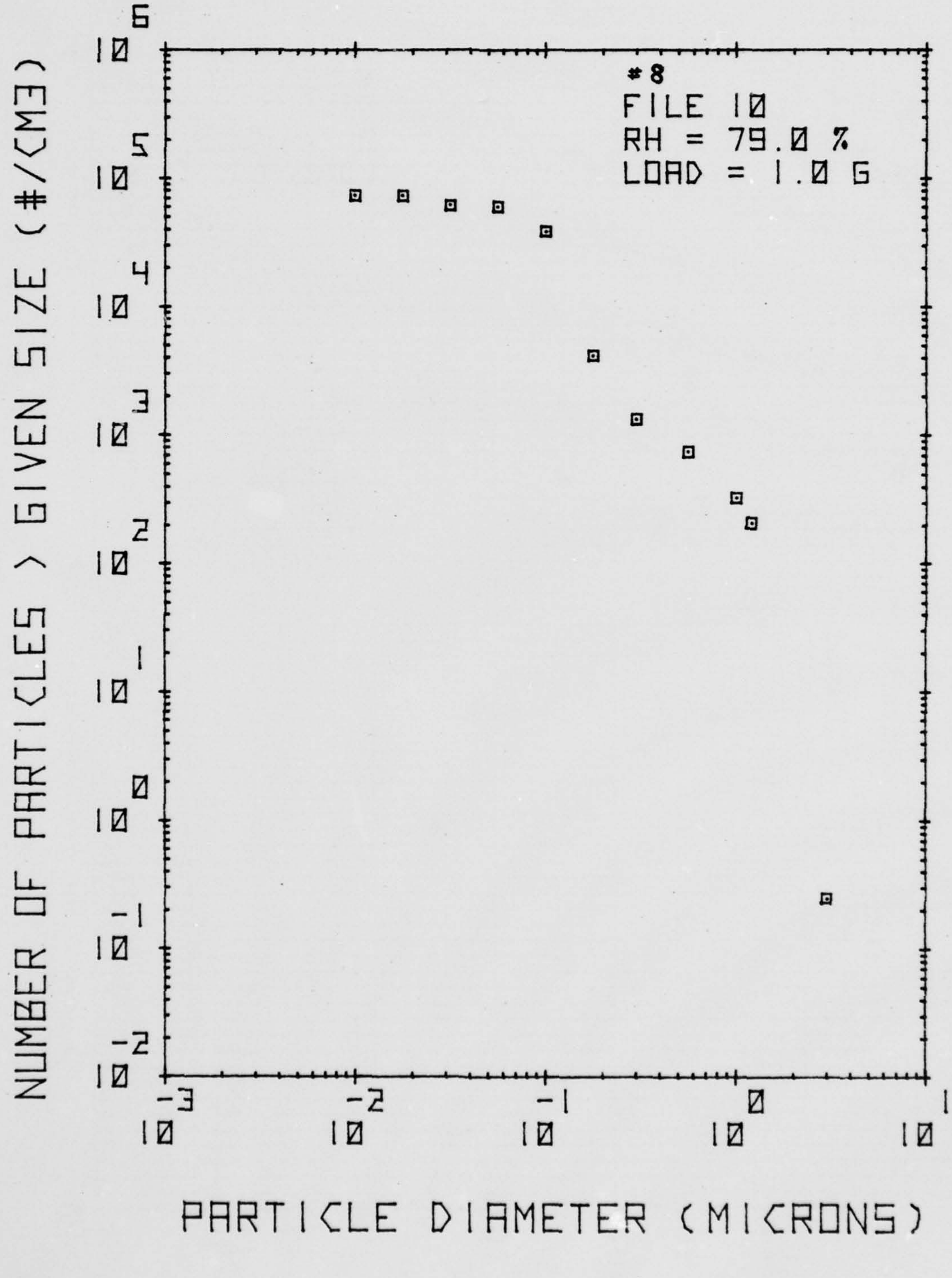
#6
FILE 17
RH = 89.0 %
LOAD = 0.1 G
NUMBER OF PARTICLES > GIVEN SIZE (#/CM3)
10^{6}
10^{5}
10^{4}
10^{3}
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
PARTICLE DIAMETER (MICRONS)



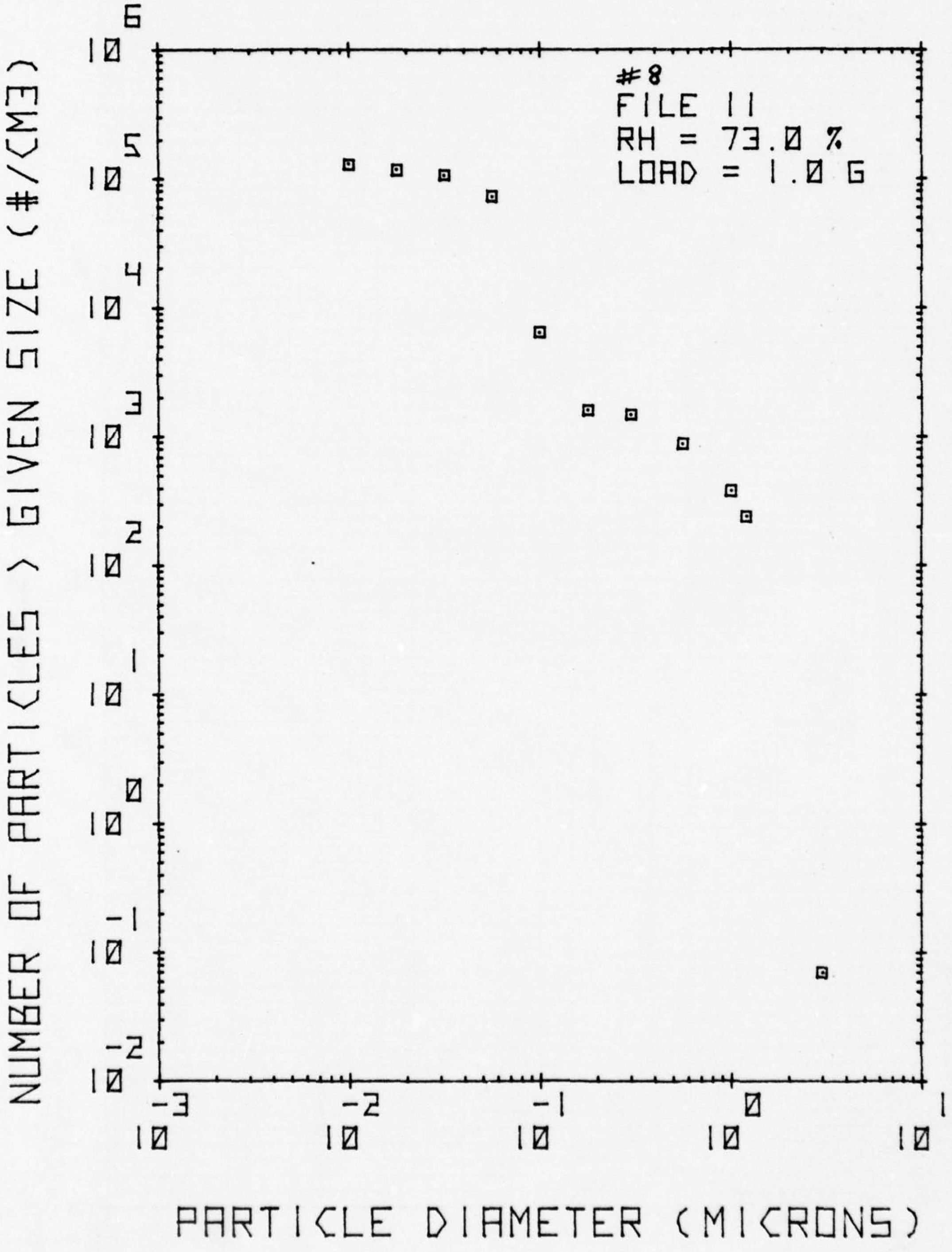
VISIBILITY AS A FUNCTION OF TIME IN EXPERIMENT #7

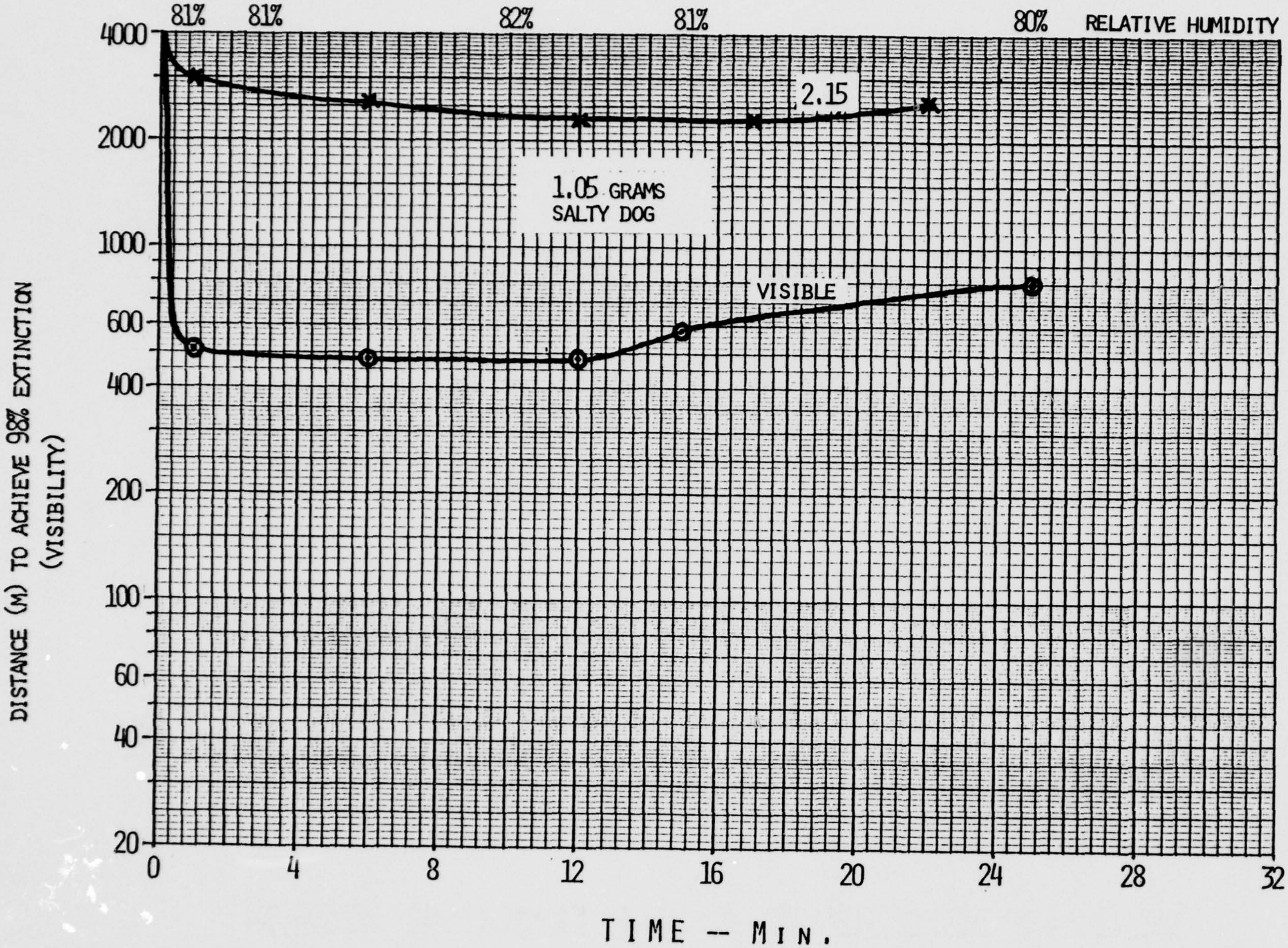


VISIBILITY AS A FUNCTION OF TIME IN EXPERIMENT #8

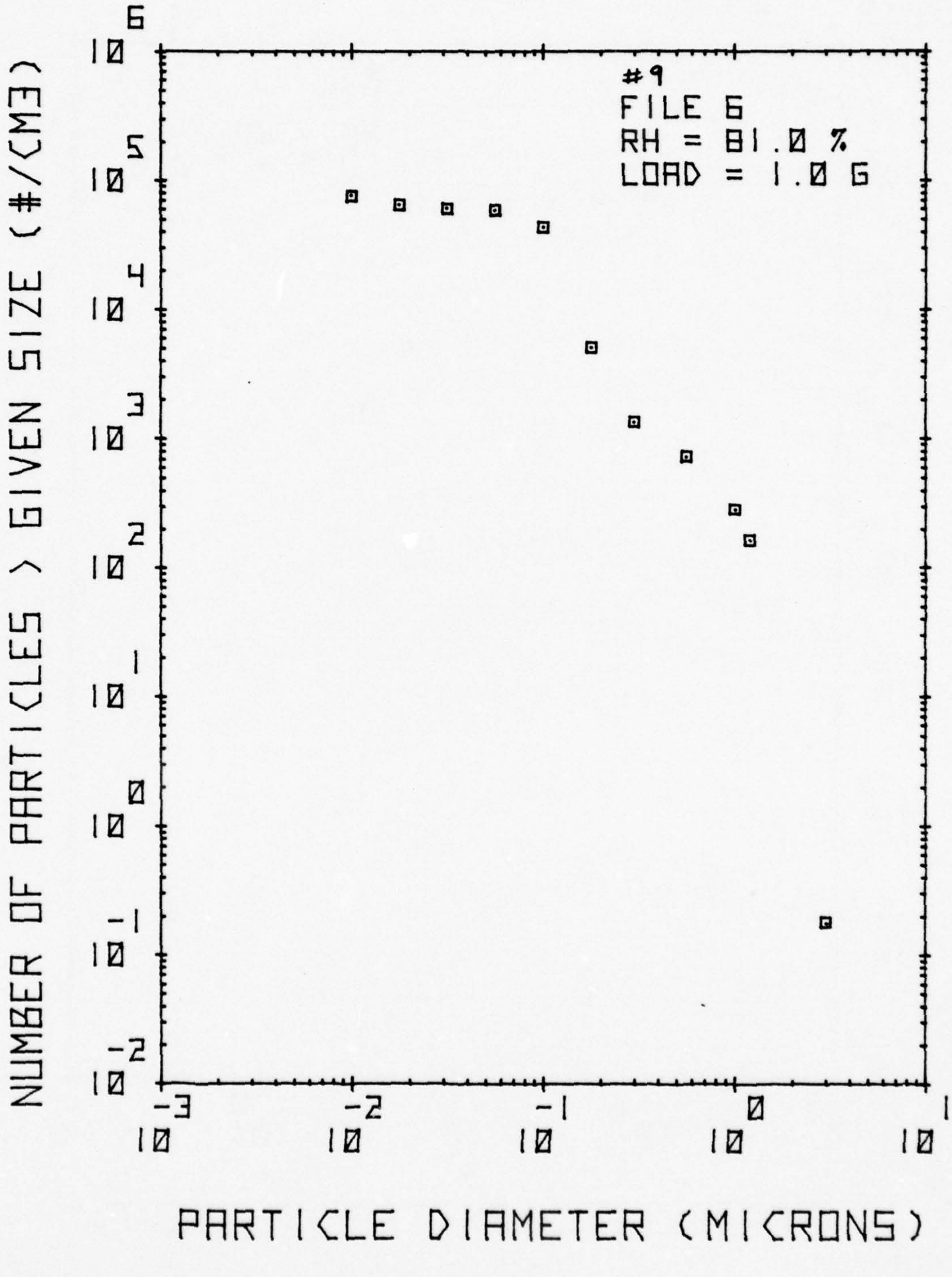


#8
FILE 10
RH = 79.0 %
LOAD = 1.0 G
NUMBER OF PARTICLES > GIVEN SIZE (#/CM3)
PARTICLE DIAMETER (MICRONS)

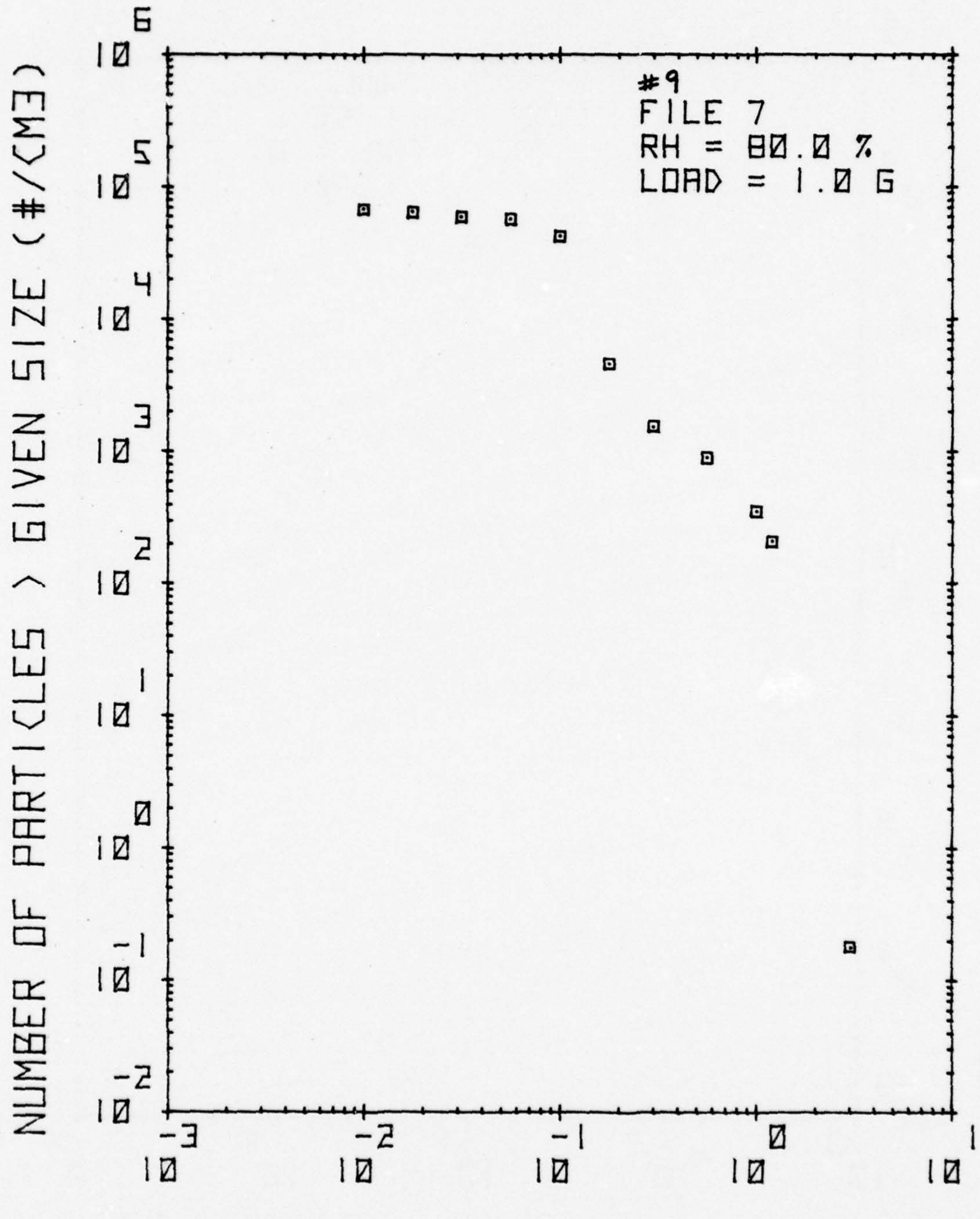

#8
FILE 11
RH = 73.0 %
LOAD = 1.0 G
NUMBER OF PARTICLES > GIVEN SIZE (#/CM3)
PARTICLE DIAMETER (MICRONS)
10^6
10^5
10^4
10^3
10^2
10^1
10^0
10^-1
10^-2
10^-3
10^-2
10^-1
10^0
10^1



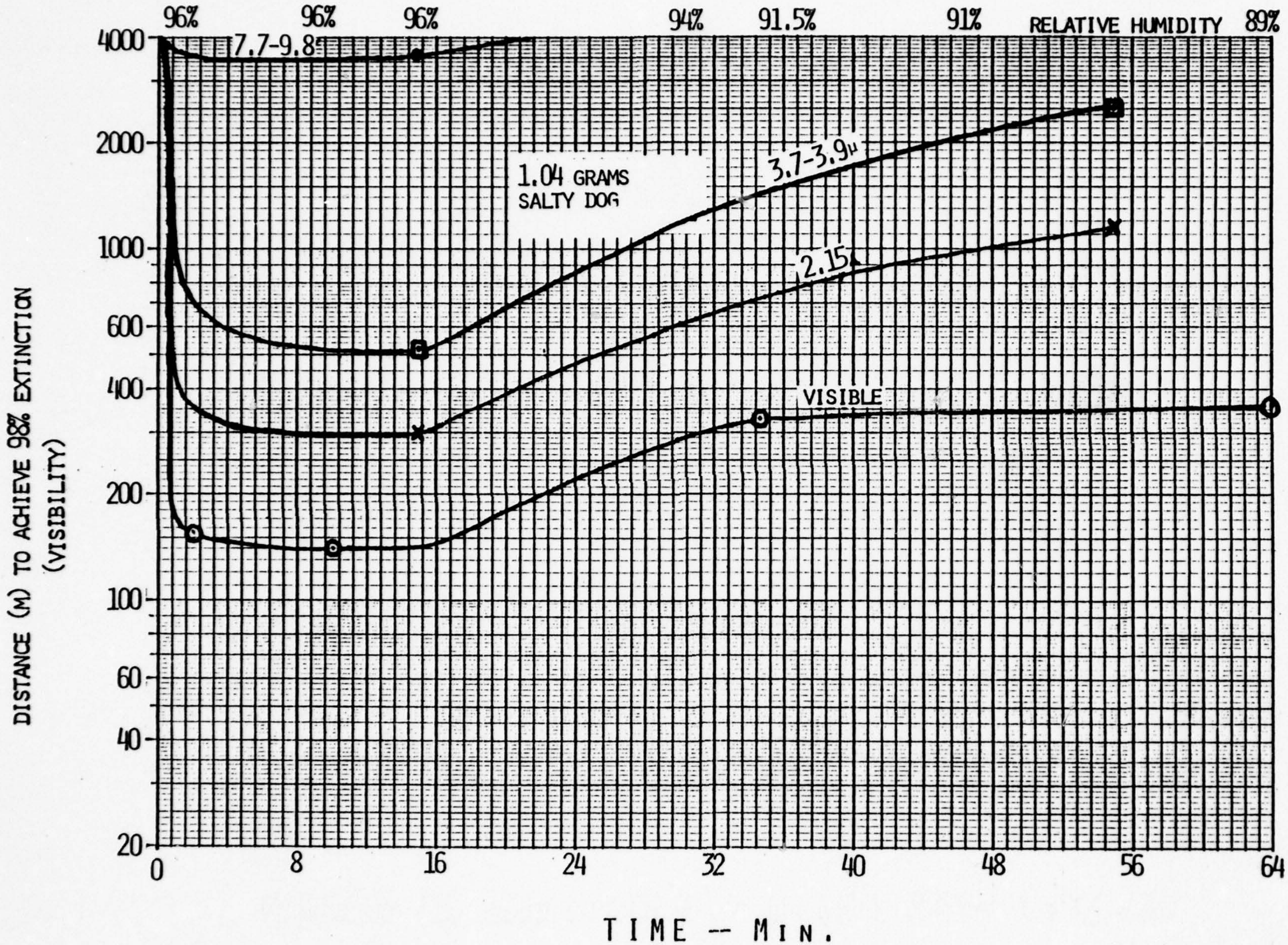
VISIBILITY AS A FUNCTION OF TIME IN EXPERIMENT #9



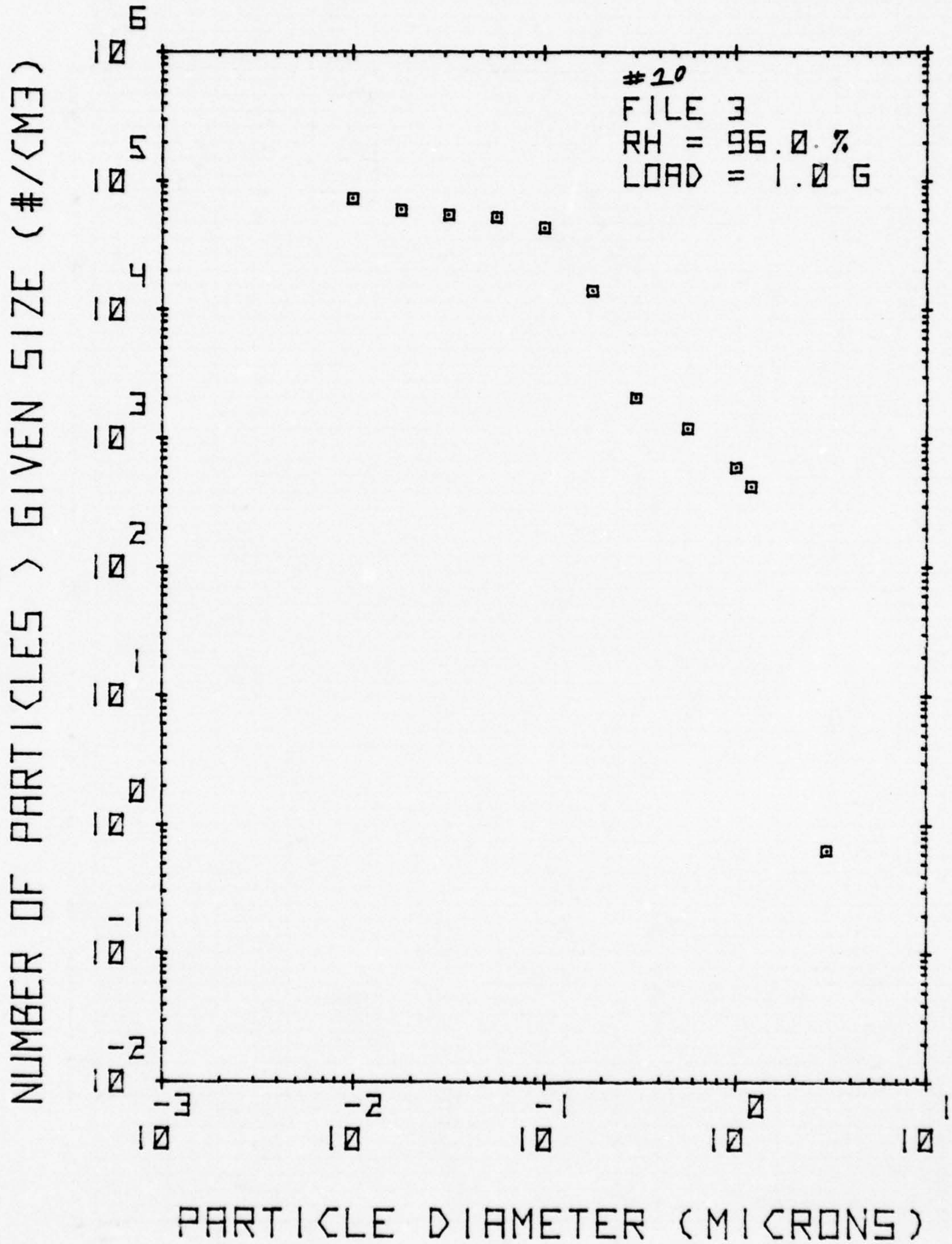
#9
FILE 6
RH = 81.0 %
LOAD = 1.0 G
NUMBER OF PARTICLES > GIVEN SIZE (#/CM3)
10^{6}
10^{5}
10^{4}
10^{3}
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
PARTICLE DIAMETER (MICRONS)



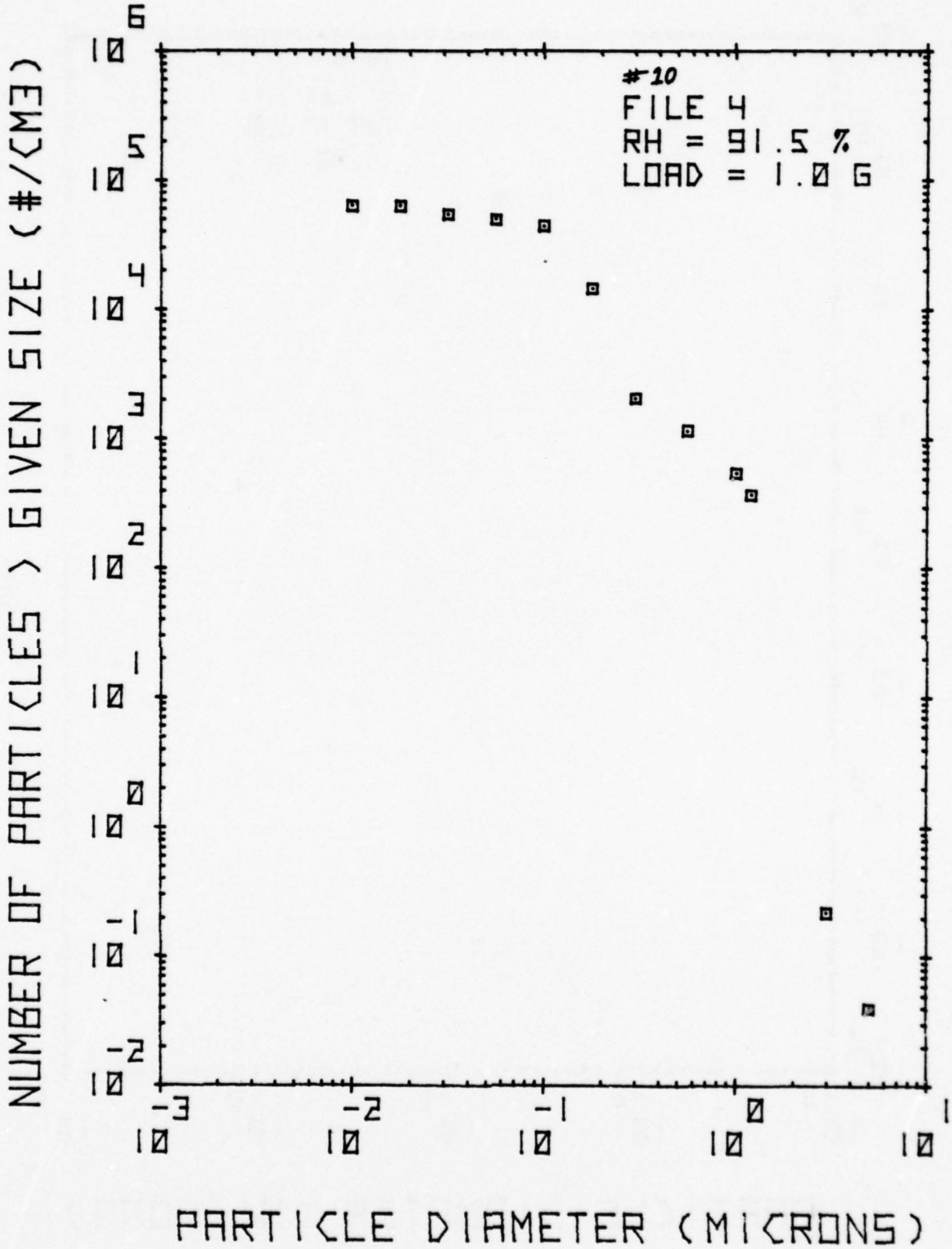
#9
FILE 7
RH = 80.0 %
LOAD = 1.0 G
NUMBER OF PARTICLES > GIVEN SIZE (#/CM3)
PARTICLE DIAMETER (MICRONS)

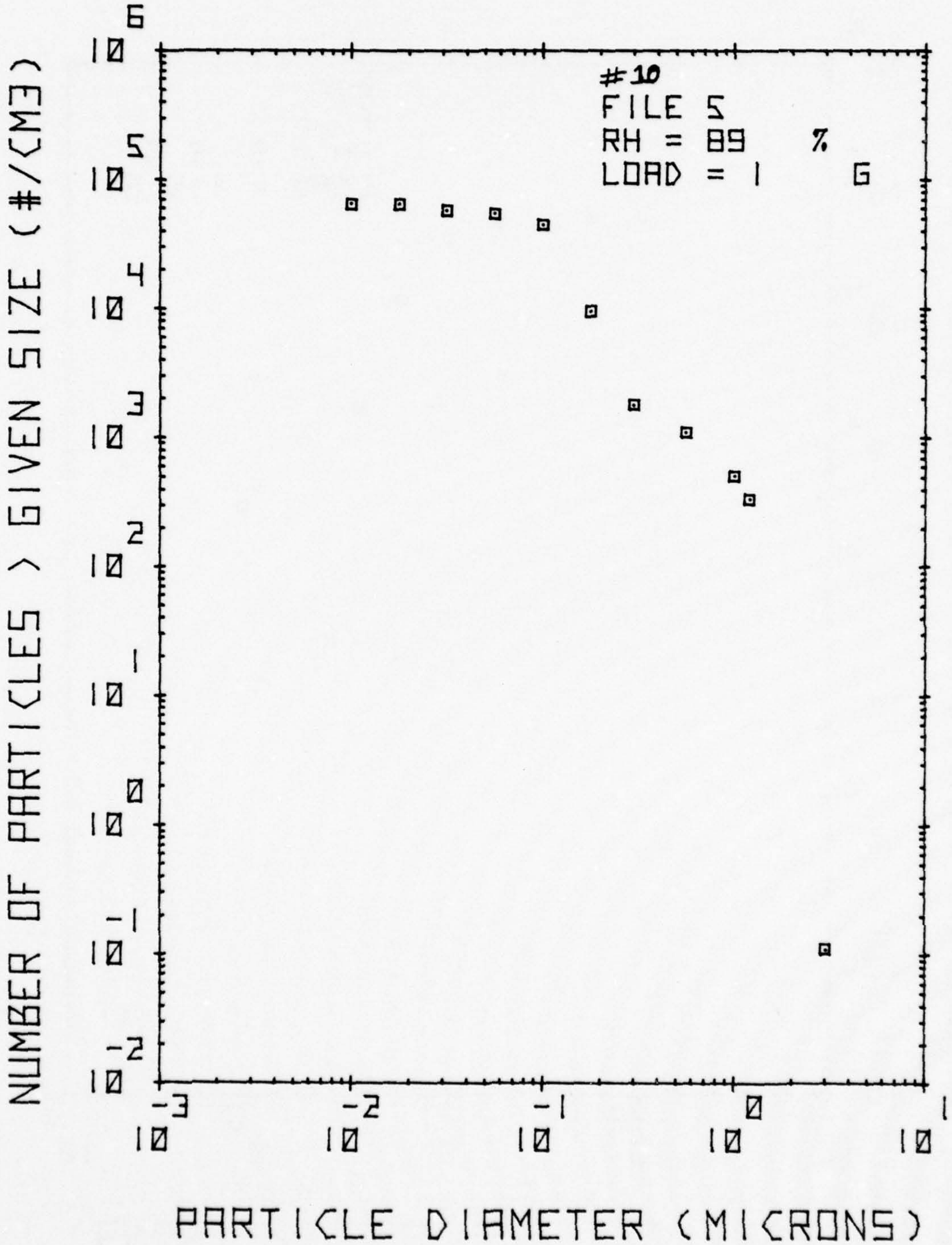


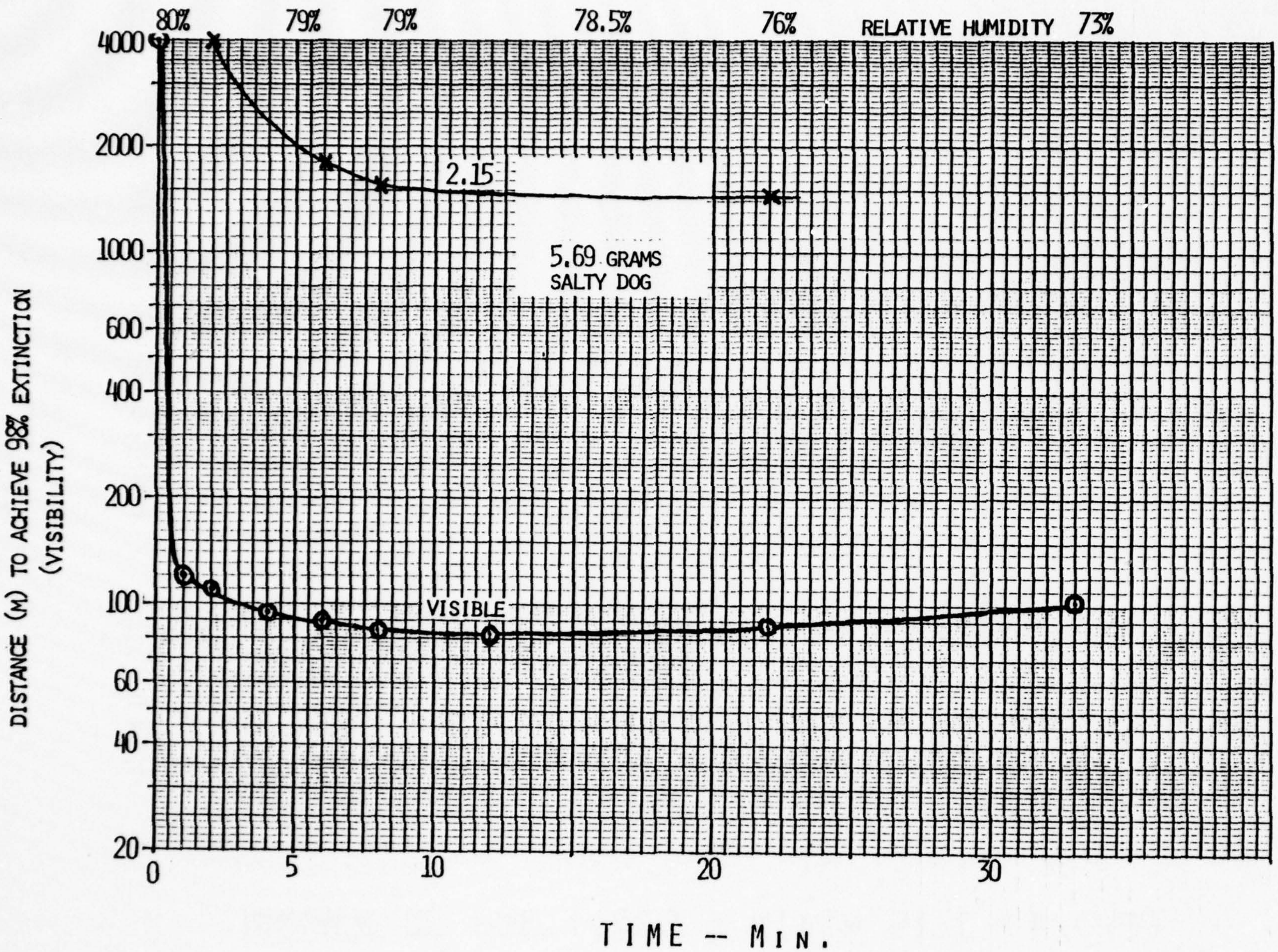
VISIBILITY AS A FUNCTION OF TIME IN EXPERIMENT #10



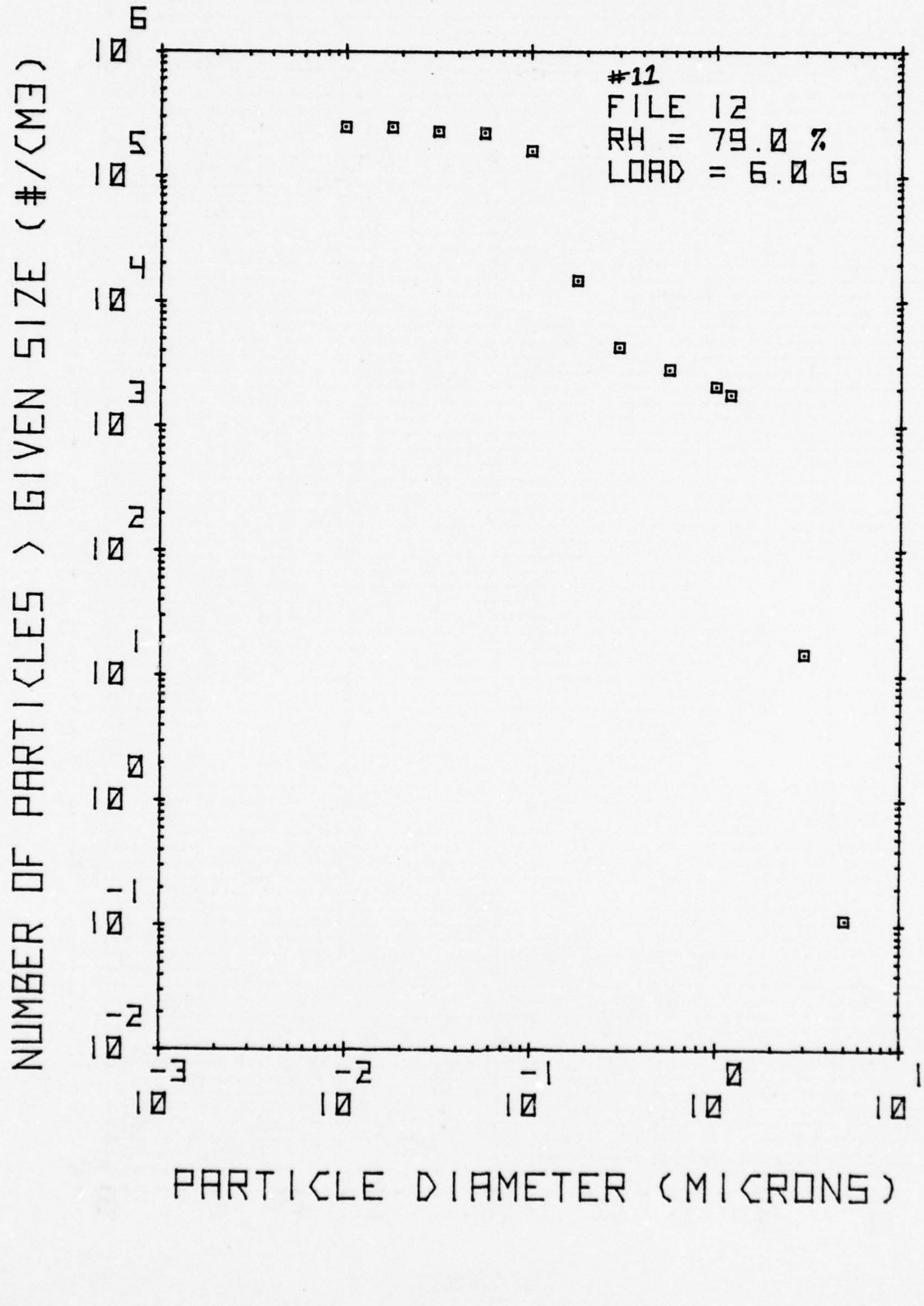
#10
FILE 3
RH = 96.0 %
LOAD = 1.0 G
NUMBER OF PARTICLES > GIVEN SIZE (#/CM3)
10^6
10^5
10^4
10^3
10^2
10^1
10^0
10^-1
10^-2
10^-3
10^-2
10^-1
10^0
10^1
PARTICLE DIAMETER (MICRONS)


#10
FILE 4
RH = 91.5 %
LOAD = 1.0 G
NUMBER OF PARTICLES > GIVEN SIZE (#/CM3)
PARTICLE DIAMETER (MICRONS)

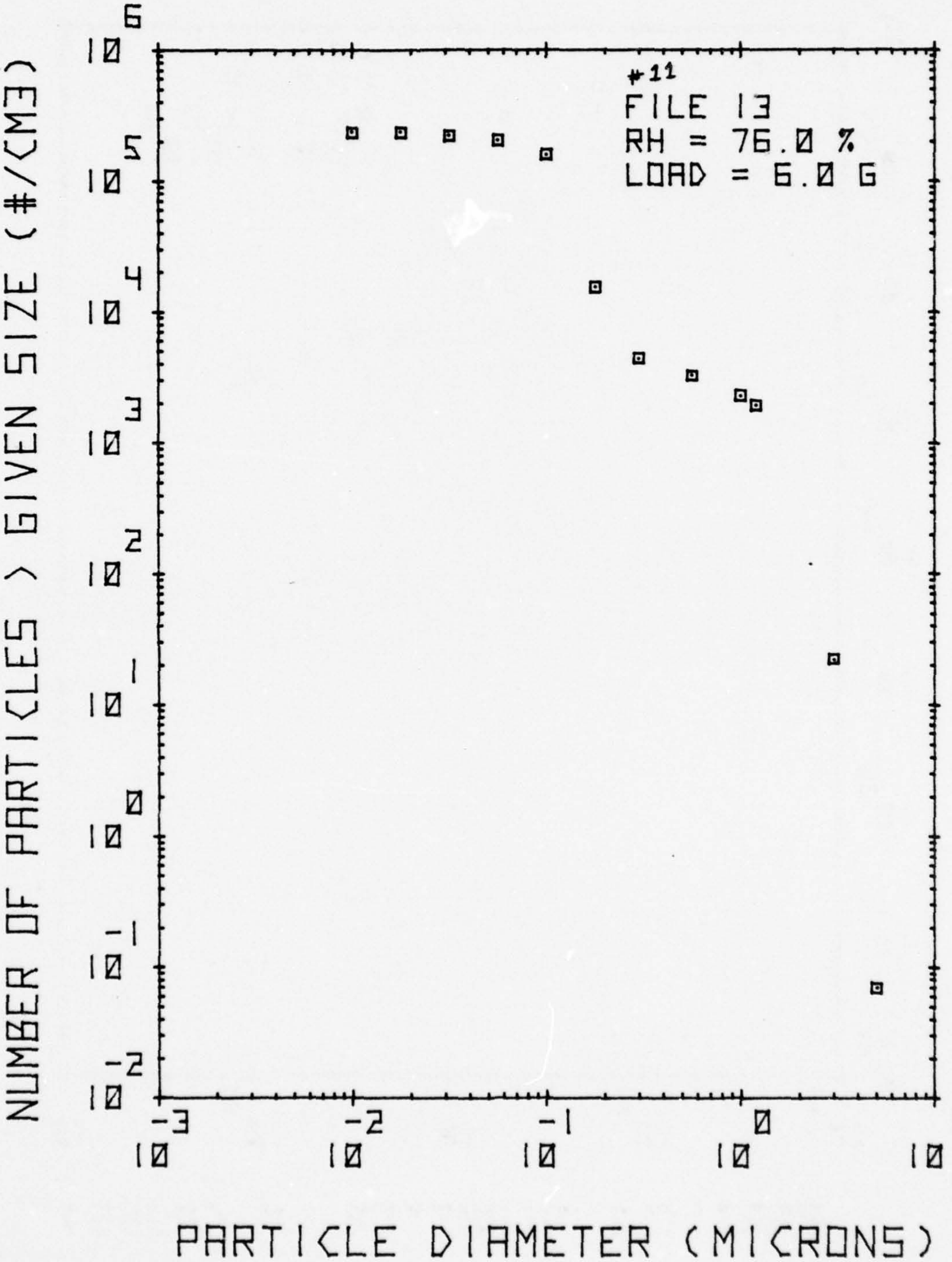

#10
FILE 5
RH = 89 %
LOAD = 1 G
NUMBER OF PARTICLES > GIVEN SIZE (#/CM3)
PARTICLE DIAMETER (MICRONS)
10^6
10^5
10^4
10^3
10^2
10^1
10^0
10^-1
10^-2
10^-3
10^-2
10^-1
10^0
10^1

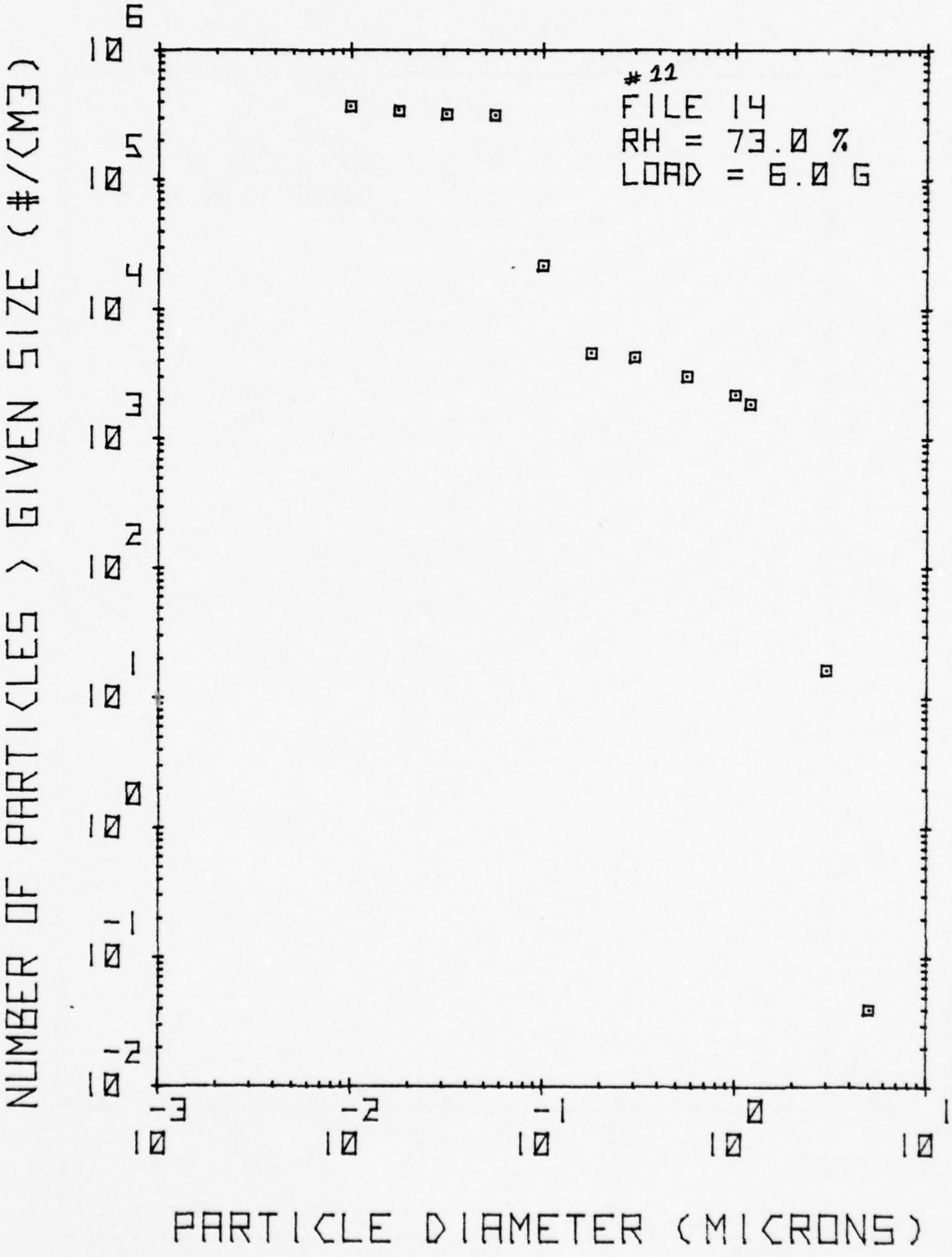


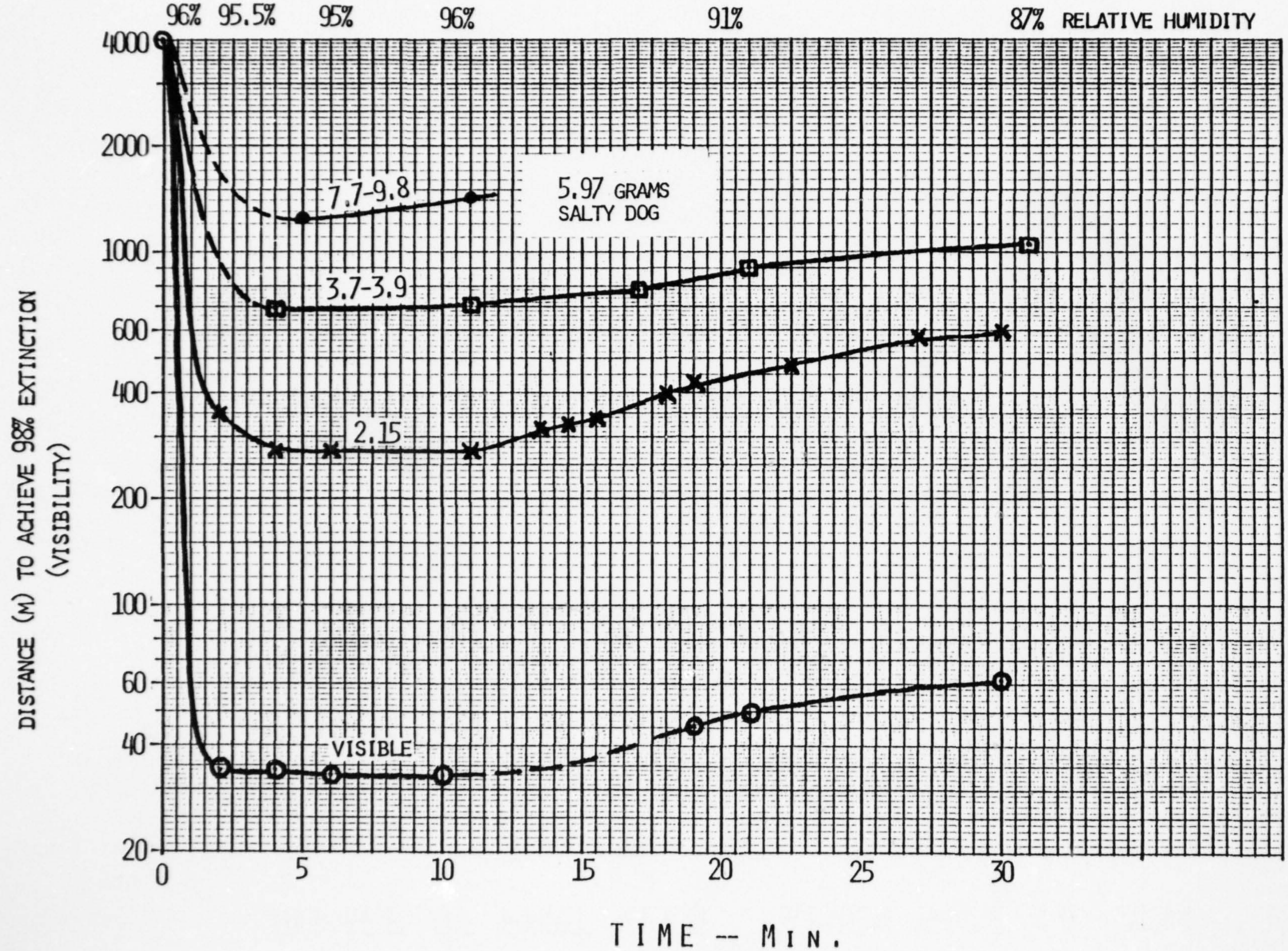
VISIBILITY AS A FUNCTION OF TIME IN EXPERIMENT #11



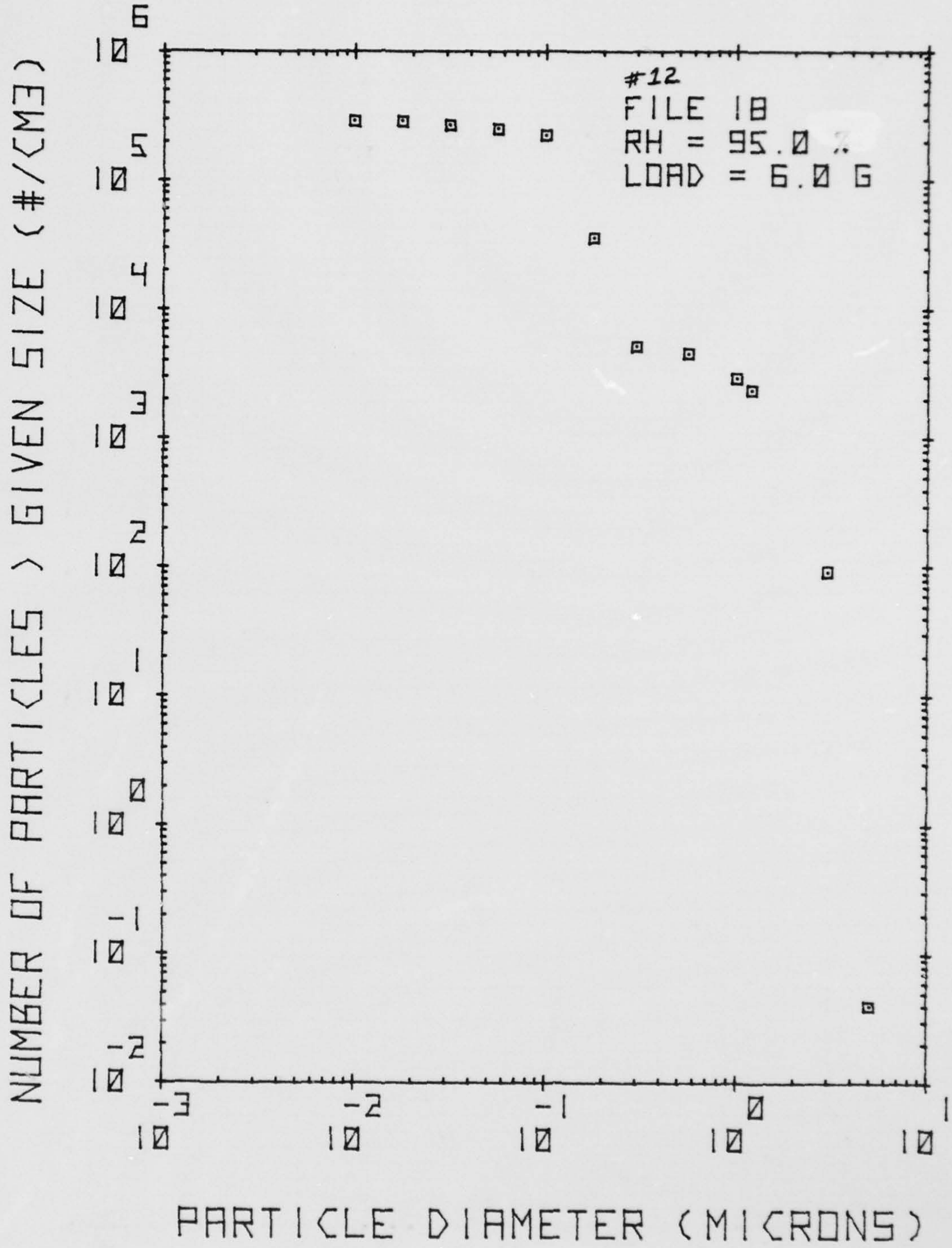
#11
FILE 12
RH = 79.0 %
LOAD = 6.0 G
NUMBER OF PARTICLES > GIVEN SIZE (#/CM3)
PARTICLE DIAMETER (MICRONS)


#11
FILE 13
RH = 76.0 %
LOAD = 6.0 G
NUMBER OF PARTICLES > GIVEN SIZE (#/CM3)
PARTICLE DIAMETER (MICRONS)
10^{6}
10^{5}
10^{4}
10^{3}
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}

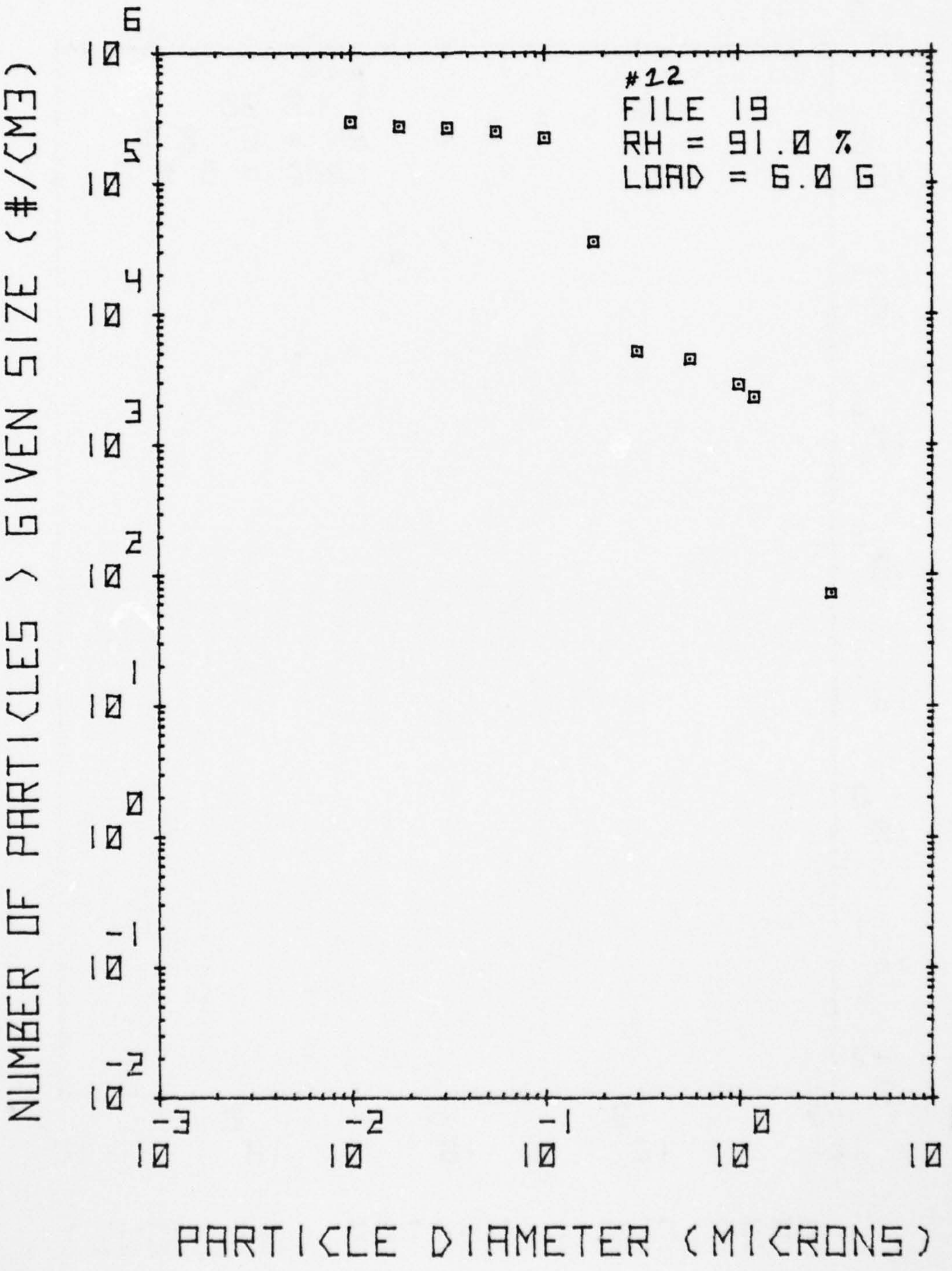

NUMBER OF PARTICLES > GIVEN SIZE (#/CM3)
PARTICLE DIAMETER (MICRONS)
#11
FILE 14
RH = 73.0 %
LOAD = 6.0 G

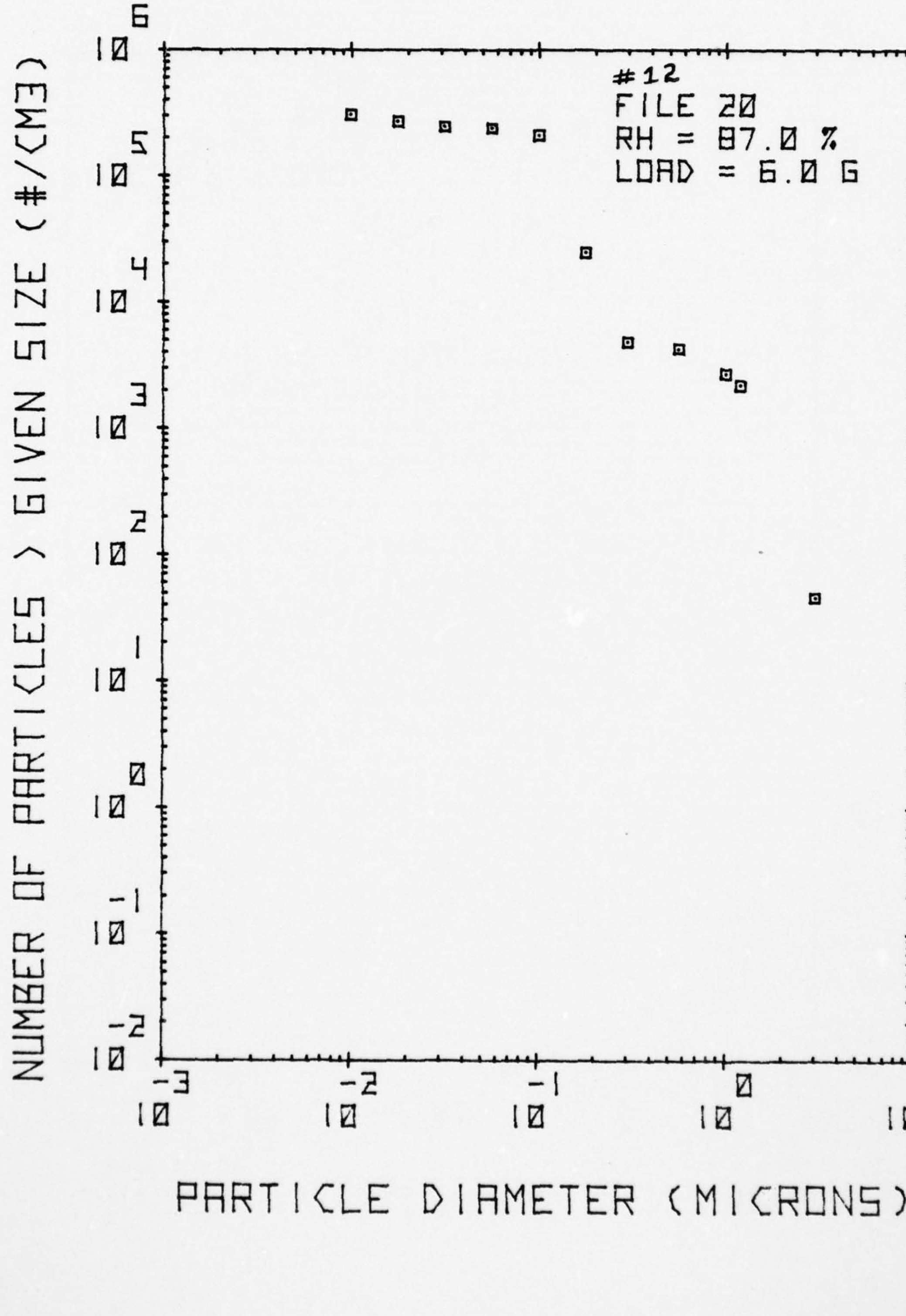


VISIBILITY AS A FUNCTION OF TIME IN EXPERIMENT #12

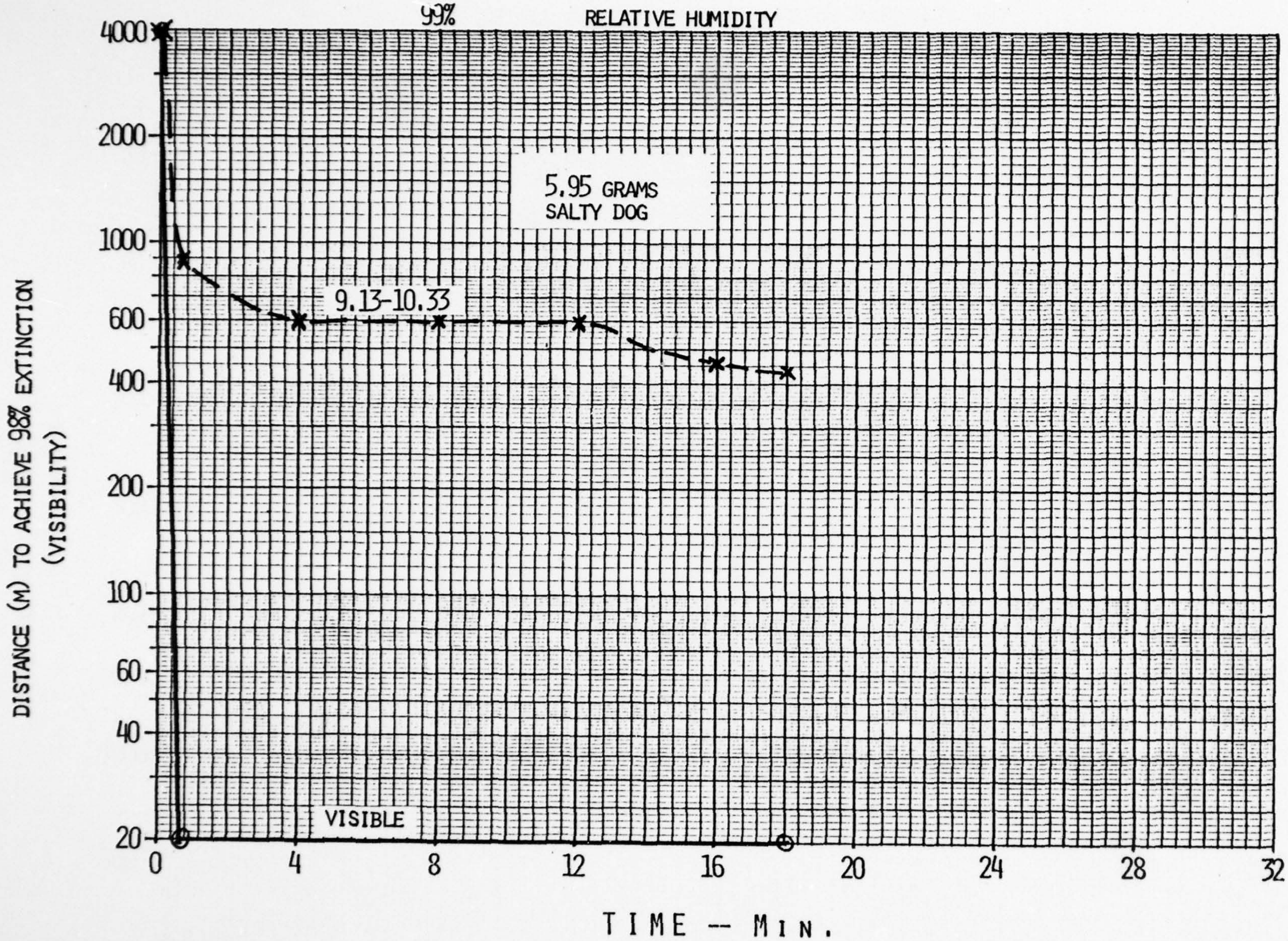


#12
FILE 18
RH = 95.0 %
LOAD = 6.0 G
NUMBER OF PARTICLES > GIVEN SIZE (#/CM3)
PARTICLE DIAMETER (MICRONS)

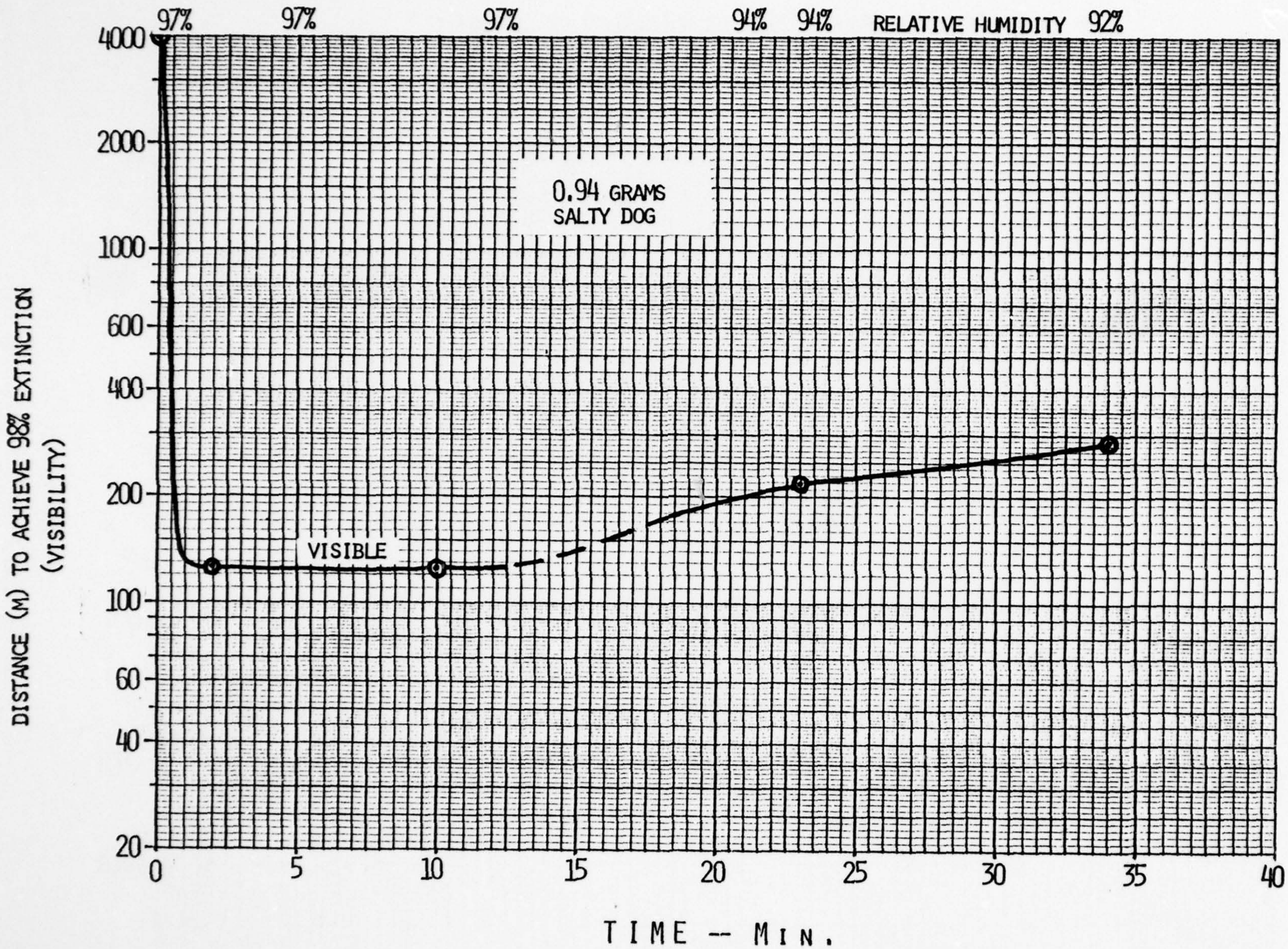

#12
FILE 19
RH = 91.0 %
LOAD = 6.0 G
NUMBER OF PARTICLES > GIVEN SIZE (#/CM3)
PARTICLE DIAMETER (MICRONS)
10^{6}
10^{5}
10^{4}
10^{3}
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}



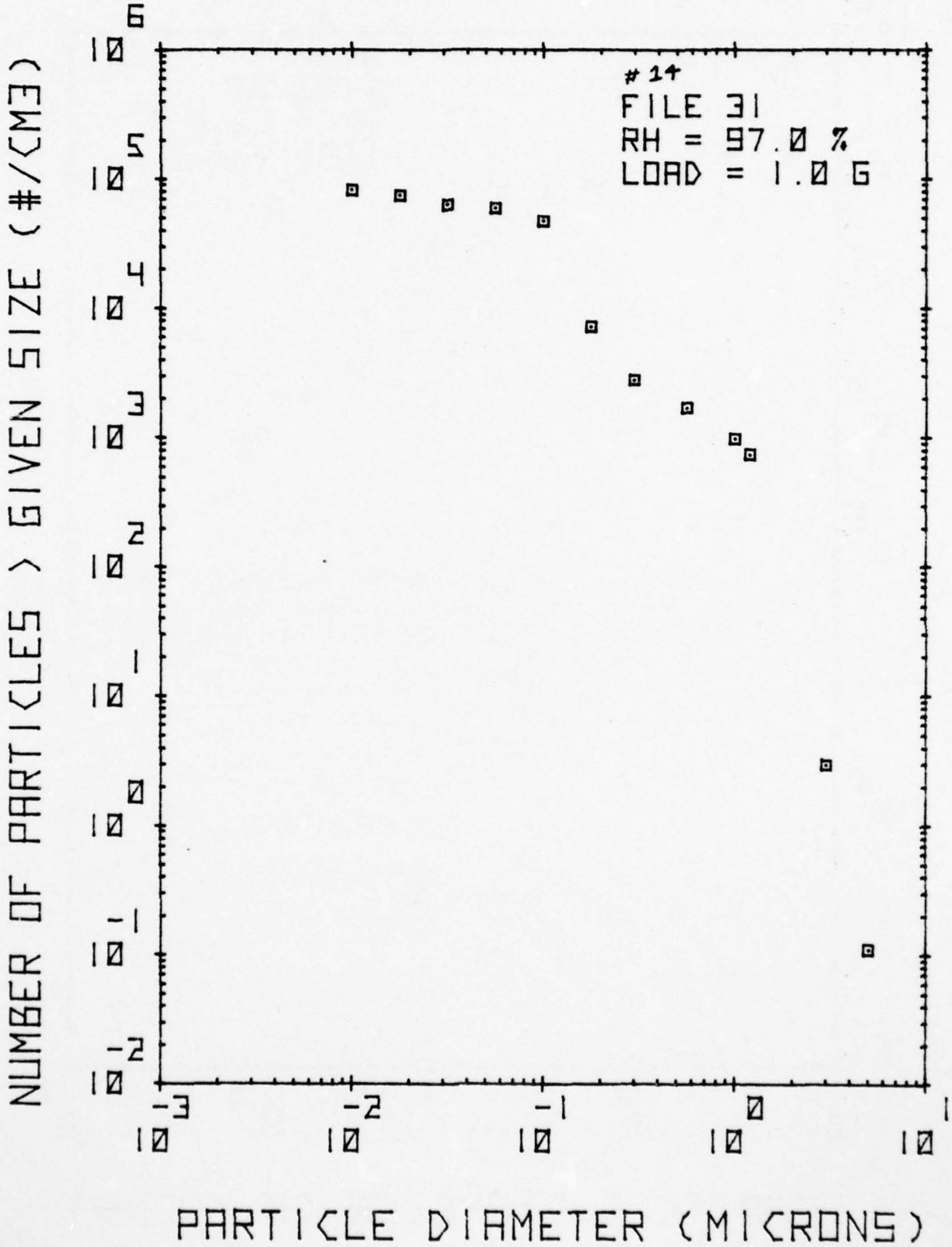
#12
FILE 20
RH = 87.0 %
LOAD = 6.0 G
NUMBER OF PARTICLES > GIVEN SIZE (#/CM3)
PARTICLE DIAMETER (MICRONS)



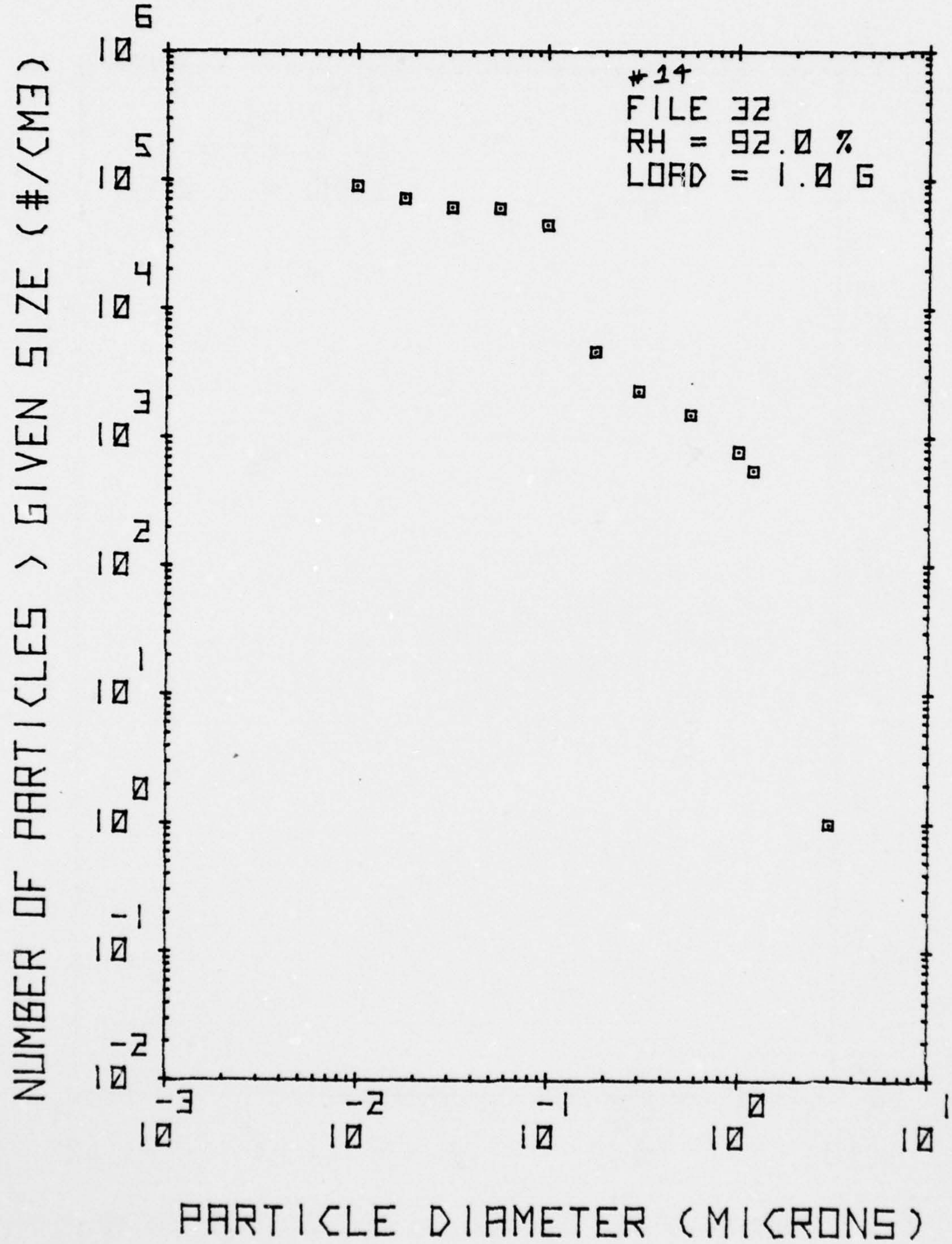
VISIBILITY AS A FUNCTION OF TIME IN EXPERIMENT #13



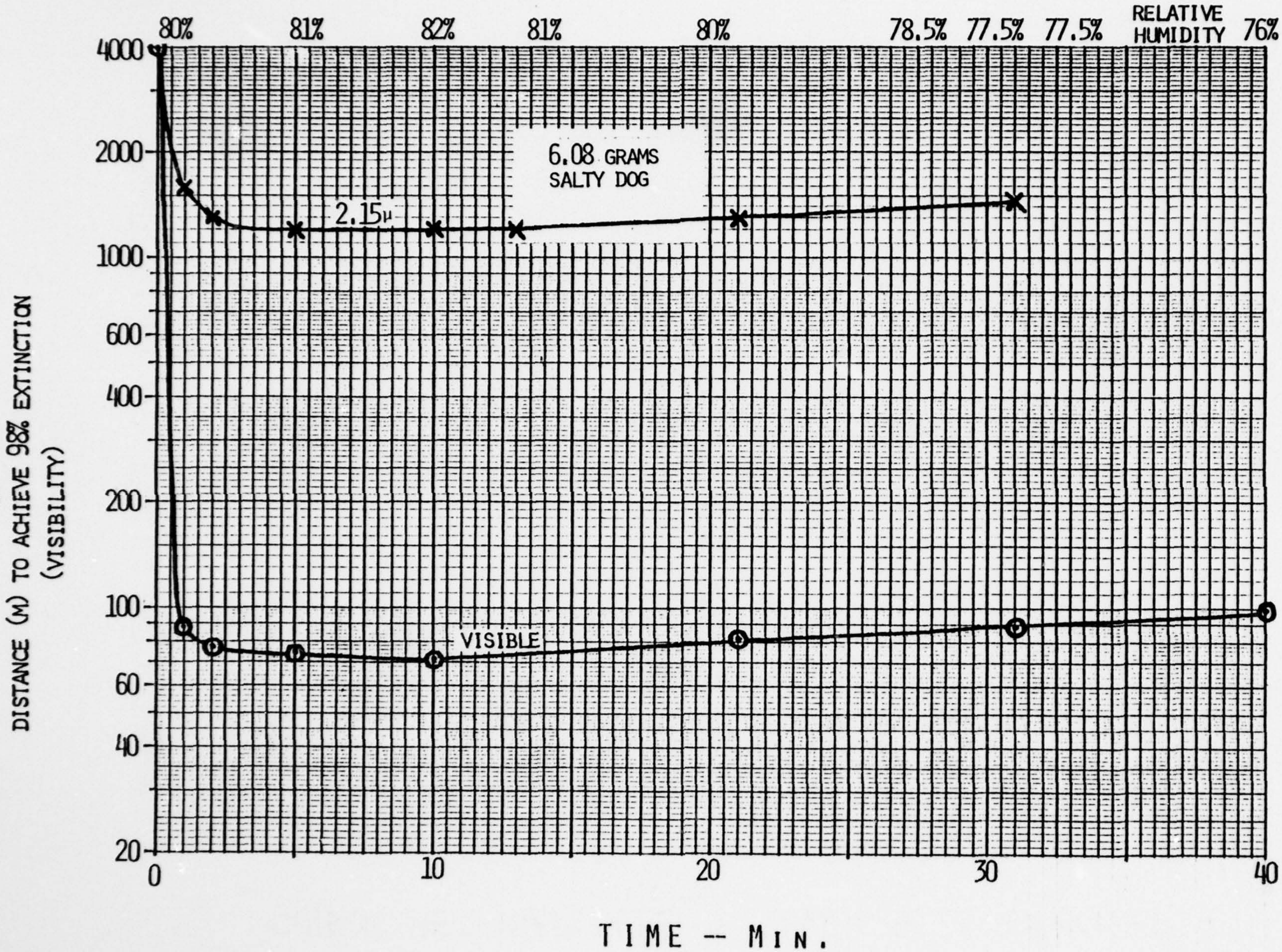
VISIBILITY AS A FUNCTION OF TIME IN EXPERIMENT #14



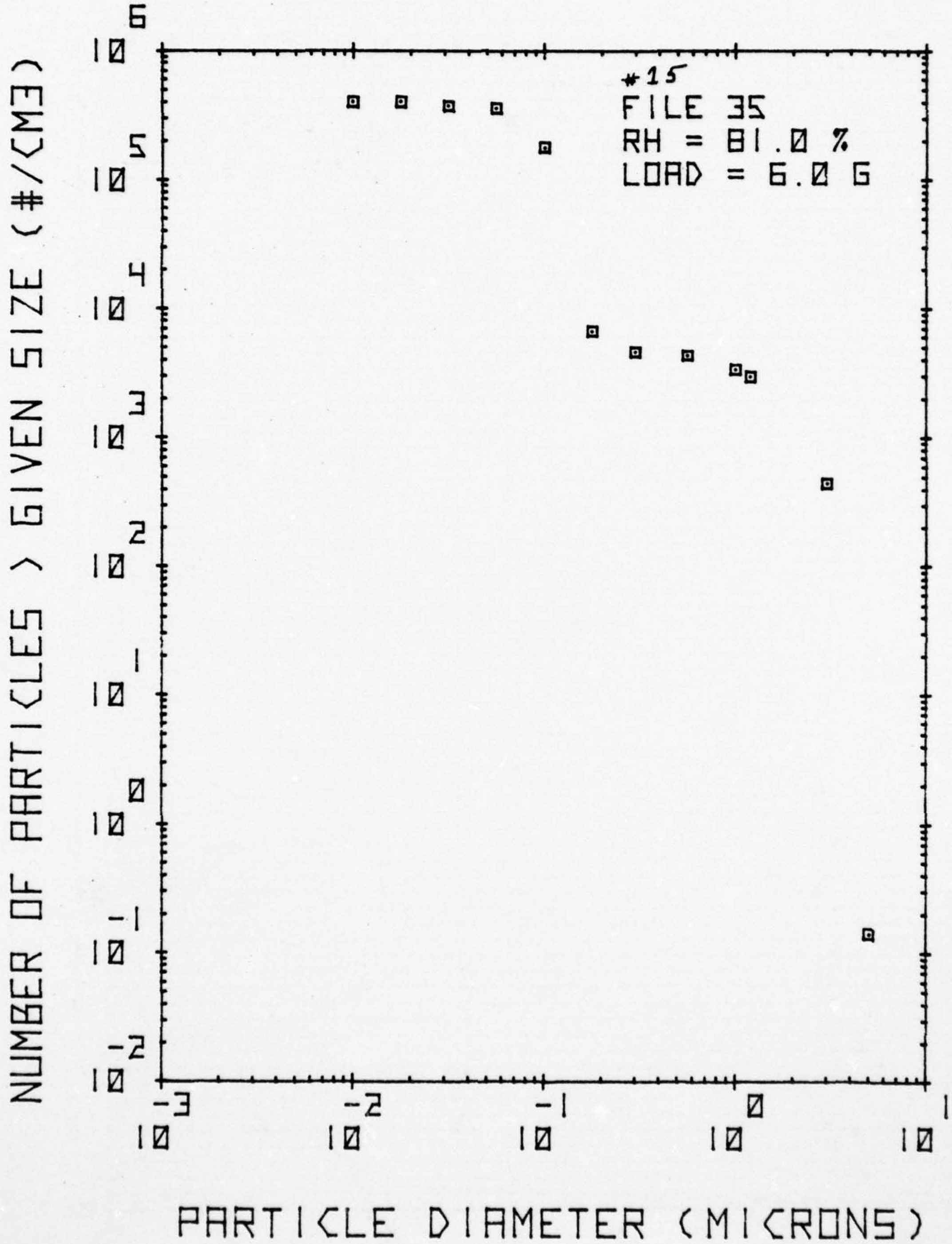
14
FILE 31
RH = 97.0 %
LOAD = 1.0 G
NUMBER OF PARTICLES > GIVEN SIZE (#/CM3)
PARTICLE DIAMETER (MICRONS)

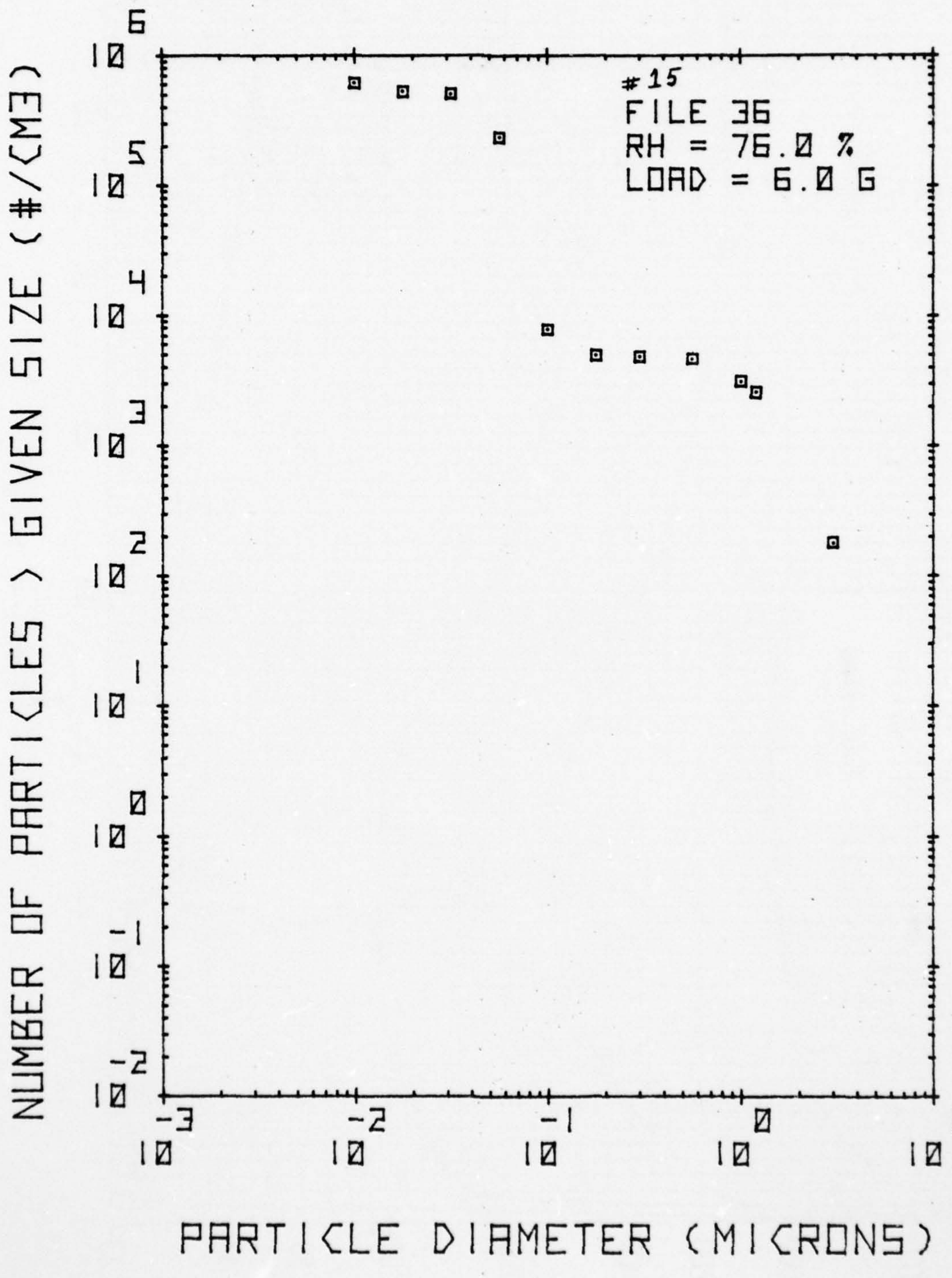


#14
FILE 32
RH = 92.0 %
LOAD = 1.0 G
NUMBER OF PARTICLES > GIVEN SIZE (#/CM3)
PARTICLE DIAMETER (MICRONS)

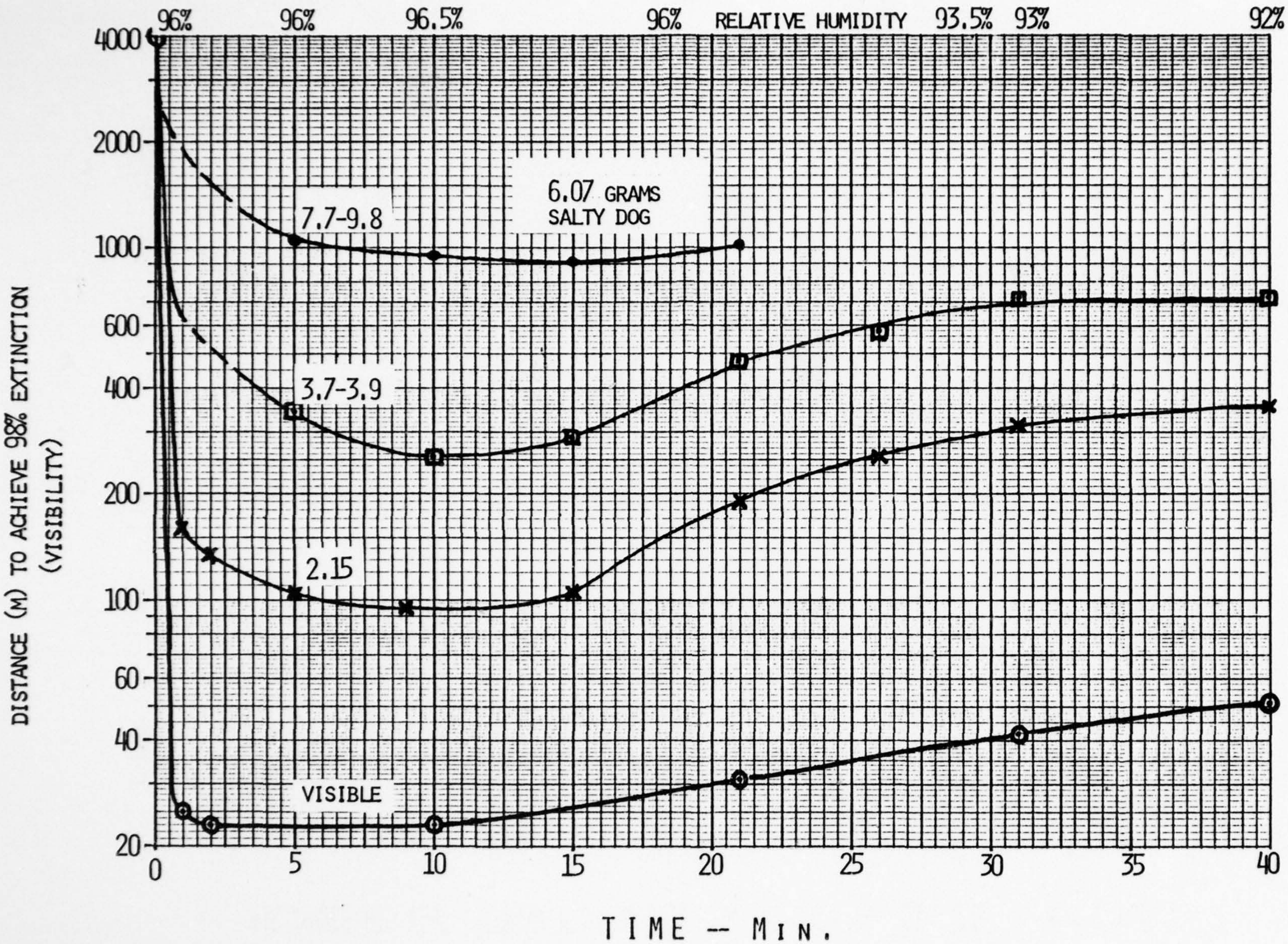


VISIBILITY AS A FUNCTION OF TIME IN EXPERIMENT #15

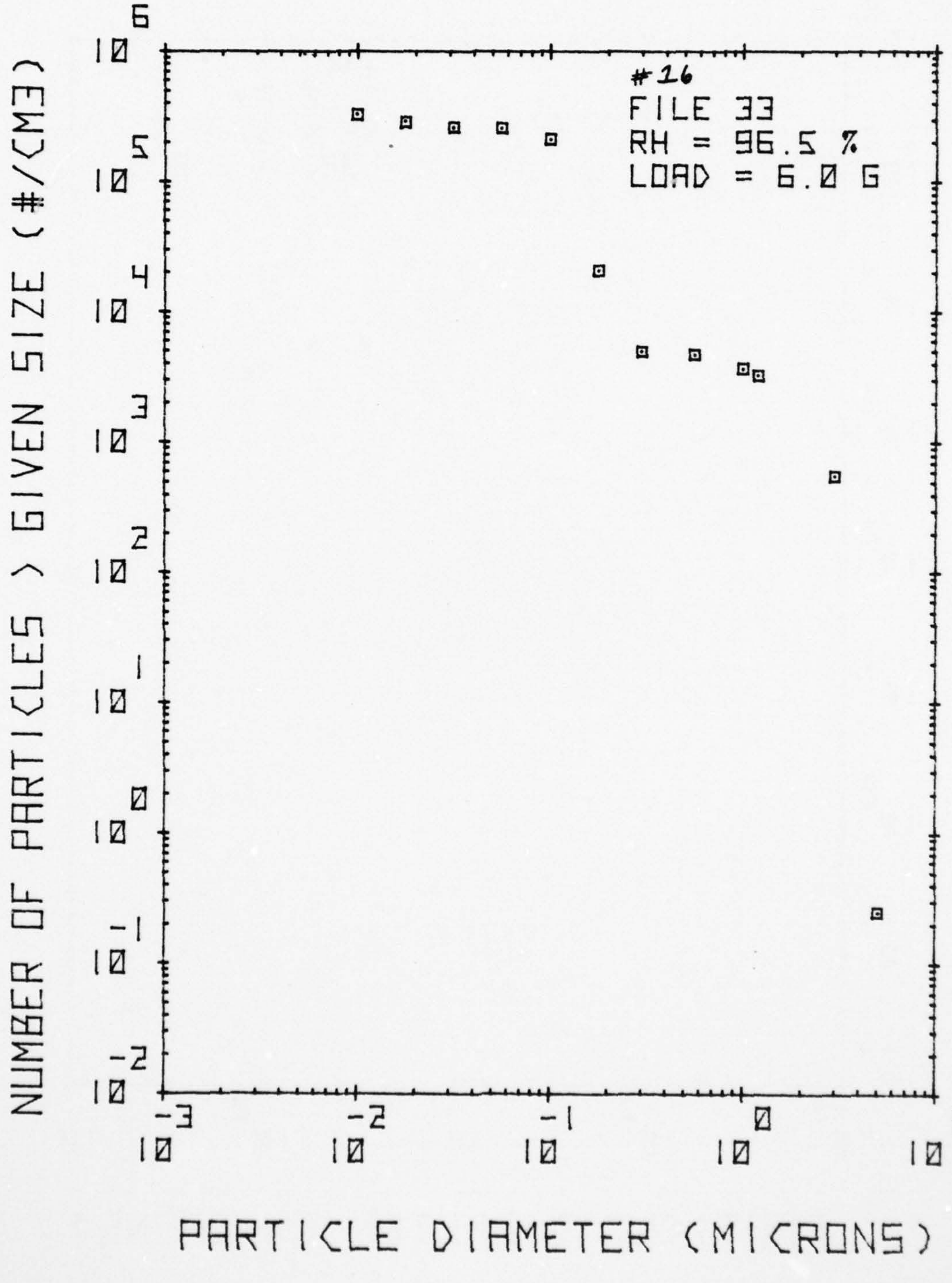

#15
FILE 35
RH = 81.0 %
LOAD = 6.0 G
NUMBER OF PARTICLES > GIVEN SIZE (#/CM3)
PARTICLE DIAMETER (MICRONS)

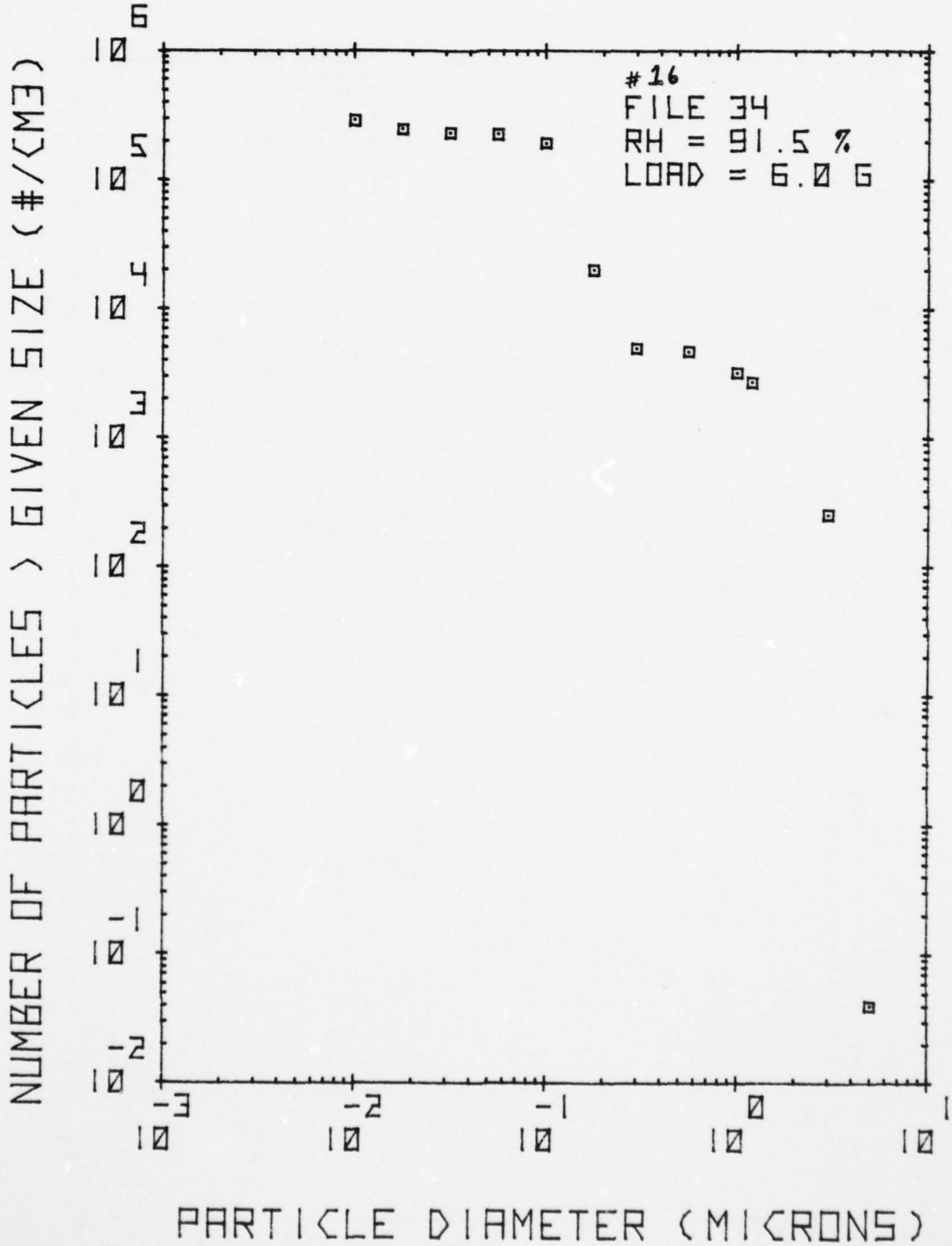


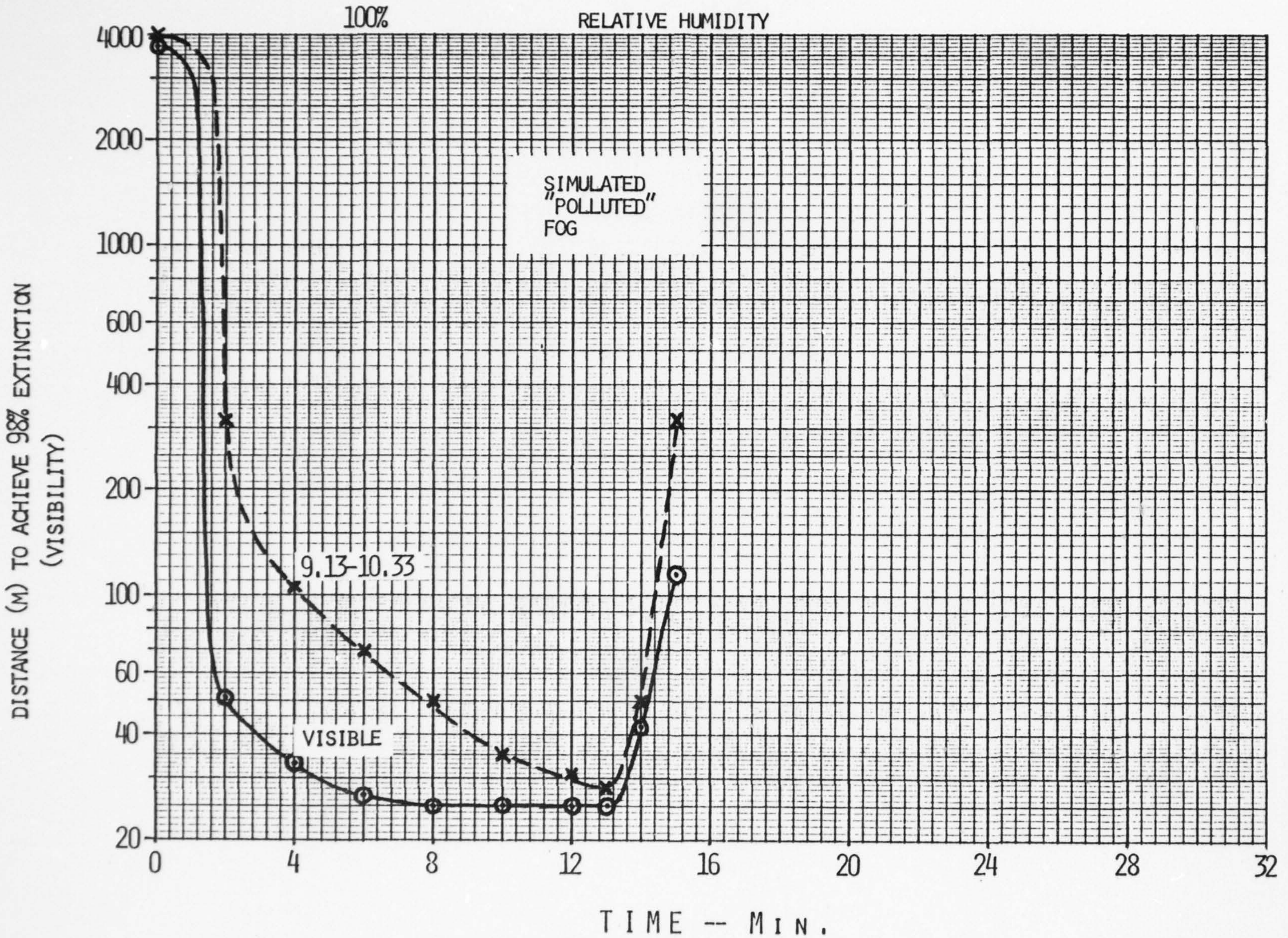
#15
FILE 36
RH = 76.0 %
LOAD = 6.0 G
NUMBER OF PARTICLES > GIVEN SIZE (#/CM3)
PARTICLE DIAMETER (MICRONS)
10^{6}
10^{5}
10^{4}
10^{3}
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}



VISIBILITY AS A FUNCTION OF TIME IN EXPERIMENT #16


#16
FILE 33
RH = 96.5 %
LOAD = 6.0 G
NUMBER OF PARTICLES > GIVEN SIZE (#/CM3)
PARTICLE DIAMETER (MICRONS)
10^{6}
10^{5}
10^{4}
10^{3}
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}


#16
FILE 34
RH = 91.5 %
LOAD = 6.0 G
NUMBER OF PARTICLES > GIVEN SIZE (#/CM3)
PARTICLE DIAMETER (MICRONS)



VISIBILITY AS A FUNCTION OF TIME IN EXPERIMENT #17

AD-A063 178 CALSPAN ADVANCED TECHNOLOGY CENTER BUFFALO NY F/G 4/2
A PRELIMINARY INVESTIGATION OF THE PRODUCTION OF STABLE FOGS UN--ETC(U)
OCT 78 E J MACK, R J ANDERSON, J T HANLEY N00019-78-C-0349
UNCLASSIFIED CALSPAN-6287-M-1 NL

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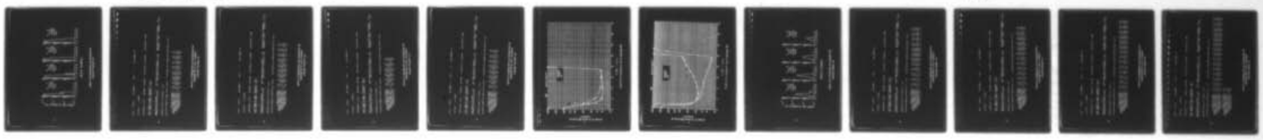

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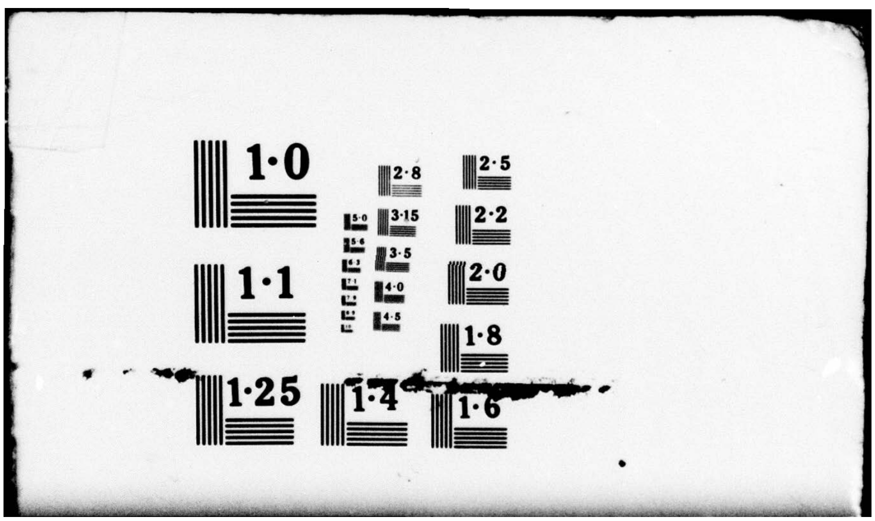
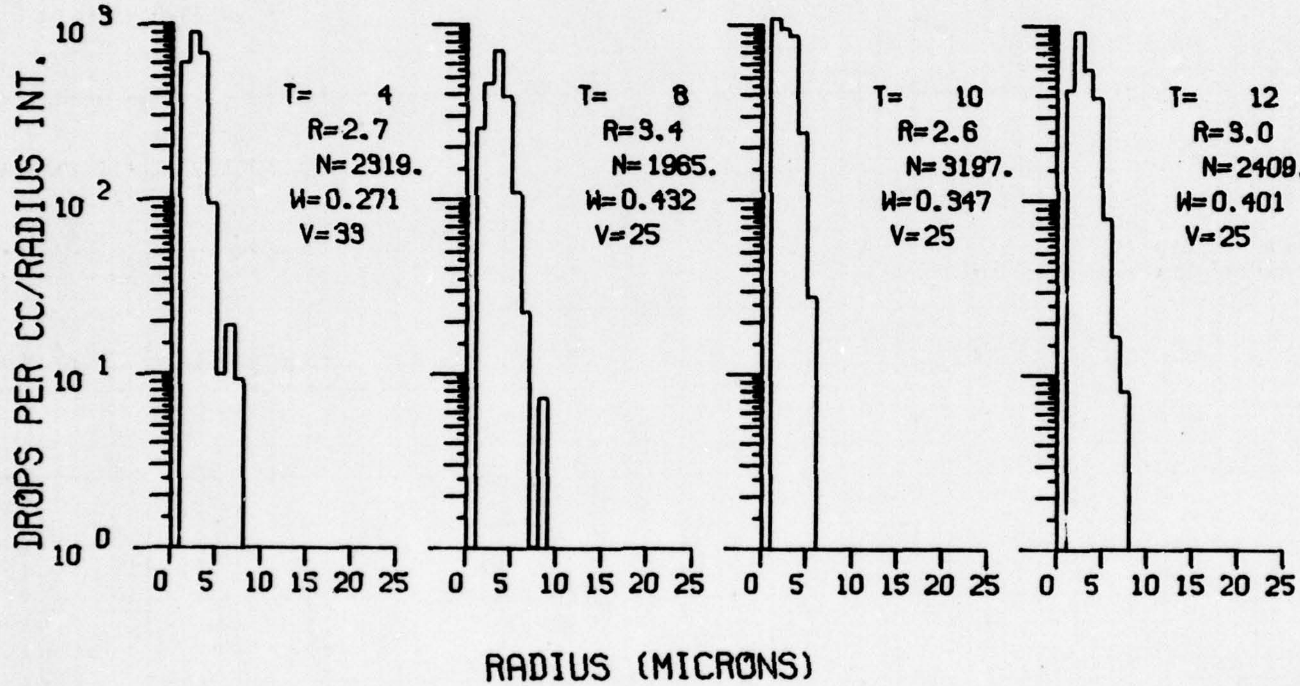

1·0
2·8
2·5
5·0
3·15
2·2
5·6
3·5
2·0
1·1
4·0
4·5
1·8
1·25
1·4
1·6



AEROSOL SIZE DISTRIBUTIONS FOR EXPERIMENT #17
SIMULATED "POLLUTED" FOG

DATE = 12JUL78 RUN NUMBER 3 TIME = 4 SLIDE NUMBER 23

ALTITUDE = 0. METERS

TEMPERATURE = 20.0C PRESSURE = 1000.0MB AIR VELOCITY = 24.6M/SEC SLIDE WIDTH = 4.0MM

TOTAL NUMBER OF DROPS (MEASURED) = 147.0
TOTAL NUMBER OF DROPS (CORRECTED) = 275.9

MEAN RADIUS IN MICRONS = 2.7 MEAN SQUARE RADIUS IN MICRONS = 2.9 MEAN VOLUME RADIUS IN MICRONS = 3.0
STANDARD DEVIATION IN MICRONS = 1.0 COEFFICIENT OF VARIATION =0.364 SKEWNESS = 1.048 KURTOSIS = 5.787

MEASURED VISIBILITY IN METERS = 33.0

CALCULATED NUMBER OF DROPS PER CC =2318.9 CALCULATED LWC IN GRAMS PER CUBIC METER = 0.271

RADIUS IN MICRONS =	0.5	1.5	2.5	3.5	4.5	5.5	6.5	7.5
MEASURED NUMBER OF DROPS =	0.0	13.0	62.0	59.0	9.0	1.0	2.0	1.0
CORRECTED NUMBER OF DROPS =	0.0	71.6	107.5	81.1	11.2	1.2	2.3	1.1
NUMBER OF DROPS PER CC =	0.0	602.1	903.5	681.4	93.9	9.8	18.9	9.2
LWC(GRAMS/CUBIC METER) =	0.0	0.009	0.059	0.122	0.036	0.007	0.022	0.016
PERCENTAGE OF DROPS =	0.0	26.0	39.0	29.4	4.0	0.4	0.8	0.4
PERCENTAGE OF LWC =	0.0	3.1	21.8	45.2	13.2	2.5	8.0	6.0

ANALYSIS OF MEASURED DROP SIZE DISTRIBUTIONS FOR
EXPERIMENT #17 AT TIME = 4 MINUTES
SIMULATED "POLLUTED" FOG

DATE = 12JUL78 RUN NUMBER 3 TIME = 8 SLIDE NUMBER 22

ALTITUDE = 0. METERS

TEMPERATURE = 20.0C PRESSURE = 1000.0MB AIR VELOCITY = 24.6M/SEC SLIDE WIDTH = 4.0MM

TOTAL NUMBER OF DROPS (MEASURED) = 190.0
TOTAL NUMBER OF DROPS (CORRECTED) = 294.2

MEAN RADIUS IN MICRONS = 3.4 MEAN SQUARE RADIUS IN MICRONS = 3.6 MEAN VOLUME RADIUS IN MICRONS = 3.7
STANDARD DEVIATION IN MICRONS = 1.2 COEFFICIENT OF VARIATION =0.346 SKEWNESS = 0.432 KURTOSIS = 3.725

MEASURED VISIBILITY IN METERS = 25.0

CALCULATED NUMBER OF DROPS PER CC =1964.5 CALCULATED LWC IN GRAMS PER CUBIC METER = 0.432

RADIUS IN MICRONS =	0.5	1.5	2.5	3.5	4.5	5.5	6.5	7.5	8.5
MEASURED NUMBER OF DROPS =	0.0	7.0	40.0	78.0	47.0	14.0	3.0	0.0	1.0
CORRECTED NUMBER OF DROPS =	0.0	38.6	69.3	107.2	58.3	16.4	3.4	0.0	1.1
NUMBER OF DROPS PER CC =	0.0	257.5	463.0	715.5	389.3	109.3	22.6	0.0	7.2
LWC(GRAMS/CUBIC METER) =	0.0	0.004	0.030	0.129	0.149	0.076	0.026	0.0	0.019
PERCENTAGE OF DROPS =	0.0	13.1	23.6	36.4	19.8	5.6	1.1	0.0	0.4
PERCENTAGE OF LWC =	0.0	0.8	7.0	29.8	34.4	17.6	6.0	0.0	4.3

ANALYSIS OF MEASURED DROP SIZE DISTRIBUTIONS FOR
EXPERIMENT #17 AT TIME = 8 MINUTES
SIMULATED "POLLUTED" FOG

DATE = 12JUL78 RUN NUMBER 3 TIME = 10 SLIDE NUMBER 21

ALTITUDE = 0. METERS

TEMPERATURE = 20.0C PRESSURE = 1000.0MB AIR VELOCITY = 20.0M/SEC SLIDE WIDTH = 4.0MM

TOTAL NUMBER OF DROPS (MEASURED) = 250.0
TOTAL NUMBER OF DROPS (CORRECTED) = 558.3

MEAN RADIUS IN MICRONS = 2.6 MEAN SQUARE RADIUS IN MICRONS = 2.8 MEAN VOLUME RADIUS IN MICRONS = 3.0
STANDARD DEVIATION IN MICRONS = 1.0 COEFFICIENT OF VARIATION =0.381 SKEWNESS = 0.458 KURTOSIS = 2.330

MEASURED VISIBILITY IN METERS = 25.0

CALCULATED NUMBER OF DROPS PER CC =3197.5 CALCULATED LWC IN GRAMS PER CUBIC METER = 0.347

RADIUS IN MICRONS =	0.5	1.5	2.5	3.5	4.5	5.5
MEASURED NUMBER OF DROPS =	0.0	22.0	85.0	106.0	33.0	4.0
CORRECTED NUMBER OF DROPS =	0.0	191.3	167.1	152.7	42.3	4.8
NUMBER OF DROPS PER CC =	0.0	1095.5	957.3	874.8	242.5	27.5
LWC(GRAMS/CUBIC METER) =	0.0	0.015	0.063	0.157	0.093	0.019
PERCENTAGE OF DROPS =	0.0	34.3	29.9	27.4	7.6	0.9
PERCENTAGE OF LWC =	0.0	4.5	18.1	45.3	26.7	5.5

ANALYSIS OF MEASURED DROP SIZE DISTRIBUTIONS FOR
EXPERIMENT #17 AT TIME = 10 MINUTES
SIMULATED "POLLUTED" FOG

DATE = 12JUL78 RUN NUMBER 3 TIME = 12 SLIDE NUMBER 20

ALTITUDE = 0. METERS

TEMPERATURE = 20.0C PRESSURE = 1000.0MB AIR VELOCITY = 20.0M/SEC SLIDE WIDTH = 4.5MM

TOTAL NUMBER OF DROPS (MEASURED) = 172.0
TOTAL NUMBER OF DROPS (CORRECTED) = 340.3

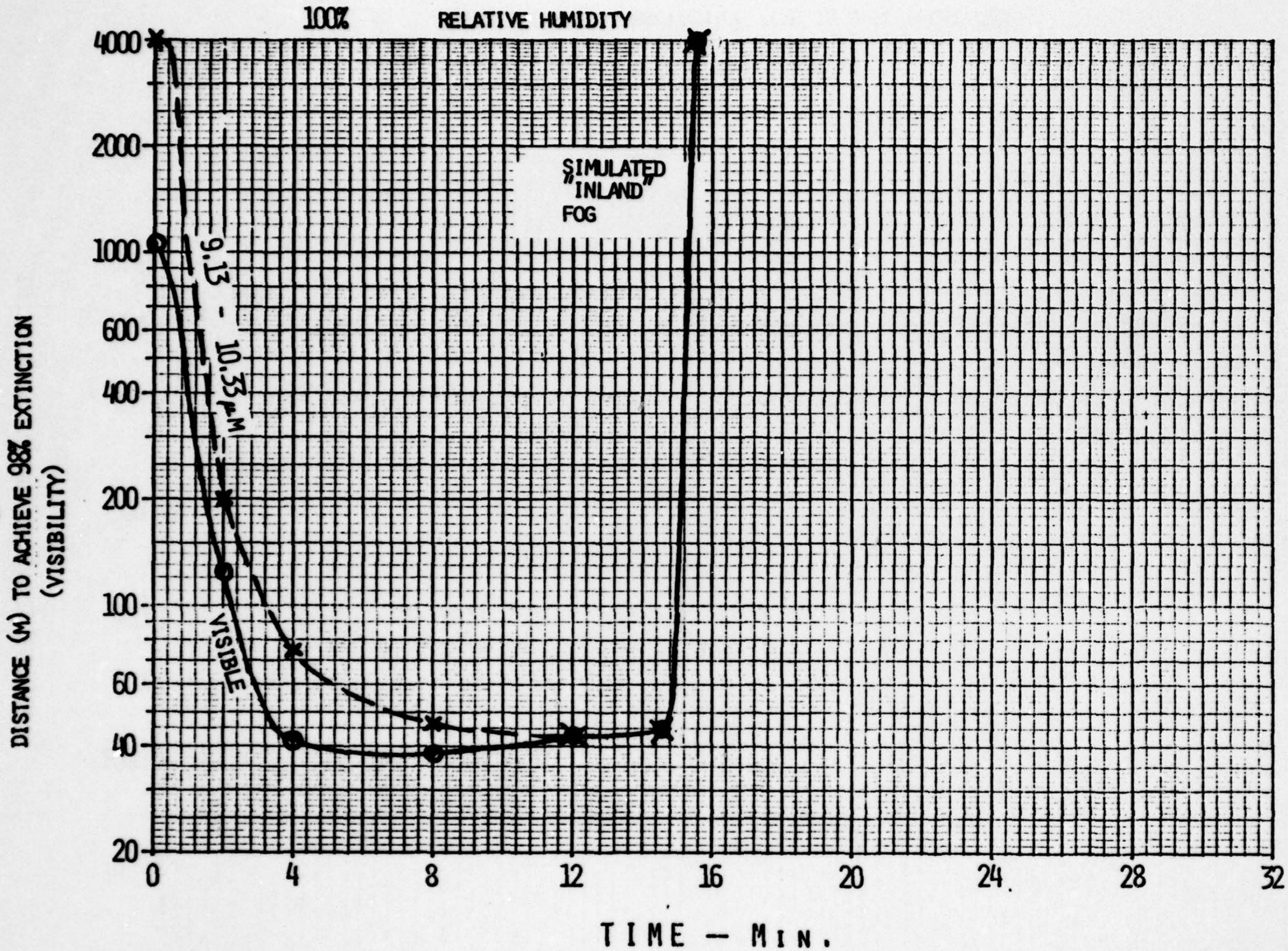
MEAN RADIUS IN MICRONS = 3.0 MEAN SQUARE RADIUS IN MICRONS = 3.2 MEAN VOLUME RADIUS IN MICRONS = 3.4
STANDARD DEVIATION IN MICRONS = 1.1 COEFFICIENT OF VARIATION =0.374 SKEWNESS = 0.677 KURTOSIS = 3.328

MEASURED VISIBILITY IN METERS = 25.0

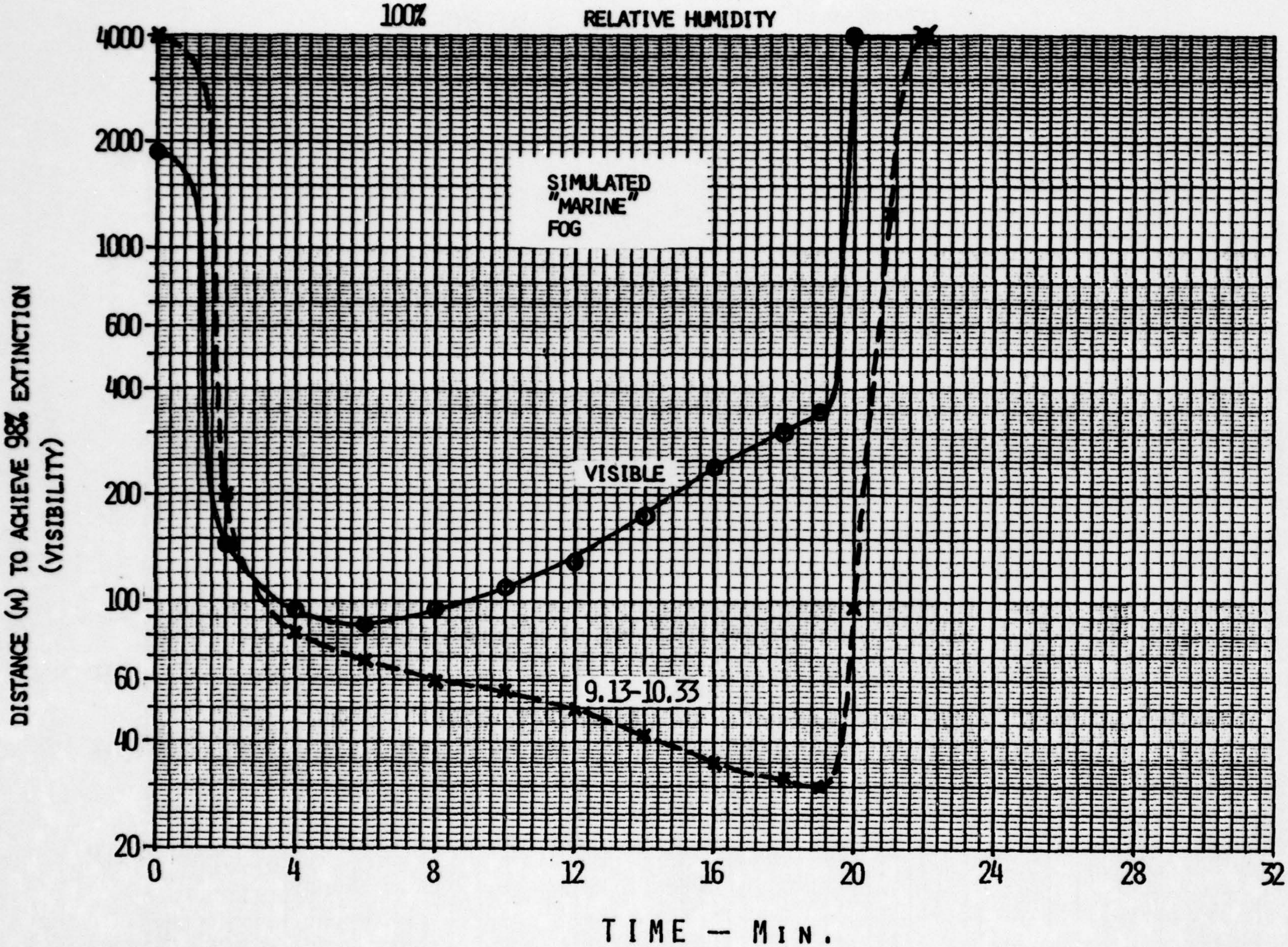
CALCULATED NUMBER OF DROPS PEK CC =2408.7 CALCULATED LWC IN GRAMS PER CUBIC METER = 0.401

RADIUS IN MICRONS =	0.5	1.5	2.5	3.5	4.5	5.5	6.5	7.5
MEASURED NUMBER OF DROPS =	0.0	5.0	61.0	53.0	41.0	9.0	2.0	1.0
CORRECTED NUMBER OF DROPS =	0.0	61.1	131.6	79.2	54.0	11.0	2.3	1.1
NUMBER OF DROPS PER CC =	0.0	432.2	931.4	560.5	382.3	77.9	16.5	8.0
LWC(GRAMS/CUBIC METER) =	0.0	0.006	0.061	0.101	0.146	0.054	0.019	0.014
PERCENTAGE OF DROPS =	0.0	17.9	38.7	23.3	15.9	3.2	0.7	0.3
PERCENTAGE OF LWC =	0.0	1.5	15.2	25.1	36.4	13.5	4.7	3.5

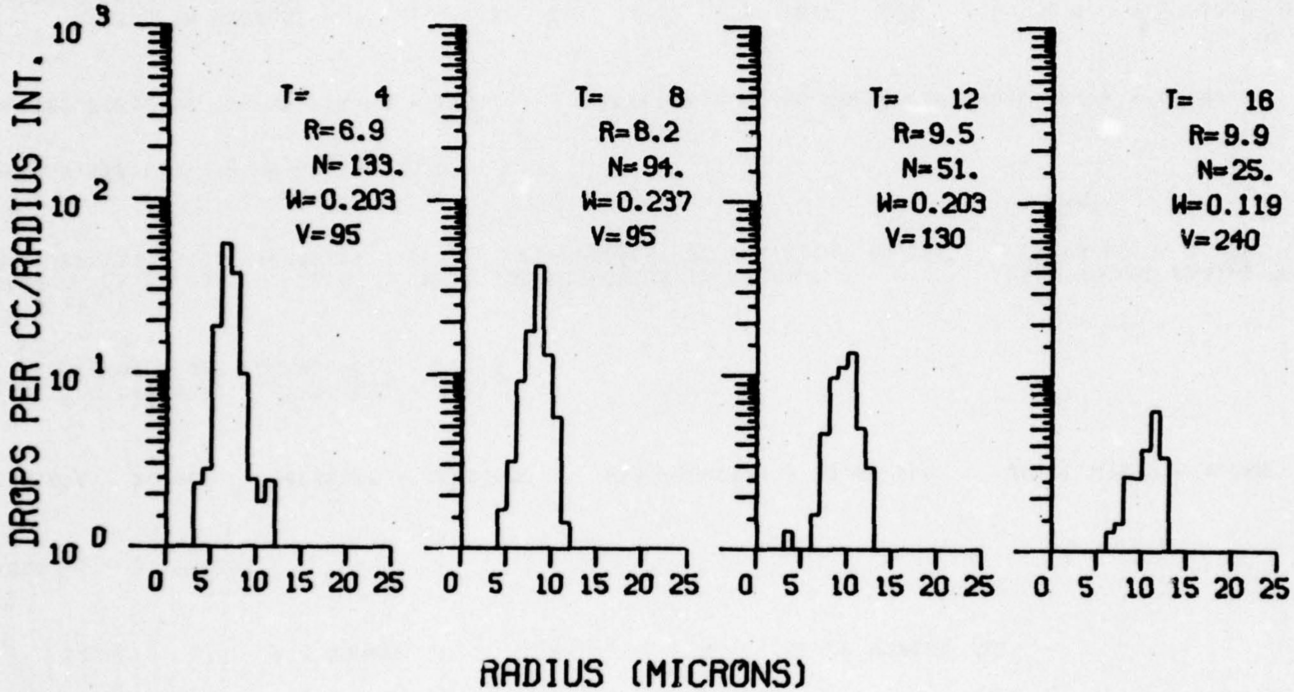
ANALYSIS OF MEASURED DROP SIZE DISTRIBUTIONS FOR
EXPERIMENT #17 AT TIME = 12 MINUTES
SIMULATED "POLLUTED" FOG



VISIBILITY AS A FUNCTION OF TIME IN EXPERIMENT #18



VISIBILITY AS A FUNCTION OF TIME IN EXPERIMENT #19



AEROSOL SIZE DISTRIBUTIONS FOR EXPERIMENT #19

SIMULATED "MARINE" FOG

DATE = 12JUL78 RUN NUMBER 1 TIME = 4 SLIDE NUMBER 36

ALTITUDE = 0. METERS

TEMPERATURE = 20.0C PRESSURE = 1000.0MB AIR VELOCITY = 29.0M/SEC SLIDE WIDTH = 4.0MM

TOTAL NUMBER OF DROPS (MEASURED) = 209.0
TOTAL NUMBER OF DROPS (CORRECTED) = 231.8

MEAN RADIUS IN MICRONS = 6.9 MEAN SQUARE RADIUS IN MICRONS = 7.0 MEAN VOLUME RADIUS IN MICRONS = 7.1
STANDARD DEVIATION IN MICRONS = 1.3 COEFFICIENT OF VARIATION =0.185 SKEWNESS = 0.825 KURTOSIS = 5.746

MEASURED VISIBILITY IN METERS = 95.0

CALCULATED NUMBER OF DROPS PER CC = 133.2 CALCULATED LWC IN GRAMS PER CUBIC METER = 0.203

RADIUS IN MICRONS =	0.5	1.5	2.5	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5
MEASURED NUMBER OF DROPS =	0.0	0.0	0.0	3.0	4.0	28.0	87.0	60.0	16.0	4.0	3.0	4.0
CORRECTED NUMBER OF DROPS =	0.0	0.0	0.0	4.0	4.8	32.2	96.8	65.3	17.1	4.2	3.1	4.2
NUMBER OF DROPS PER CC =	0.0	0.0	0.0	2.3	2.8	18.5	55.6	37.5	9.9	2.4	1.8	2.4
LWC(GRAMS/CUBIC METER) =	0.0	0.0	0.0	0.000	0.001	0.013	0.064	0.066	0.025	0.009	0.009	0.015
PERCENTAGE OF DROPS =	0.0	0.0	0.0	1.7	2.1	13.9	41.8	28.2	7.4	1.8	1.4	1.8
PERCENTAGE OF LWC =	0.0	0.0	0.0	0.2	0.5	6.4	31.6	32.7	12.5	4.3	4.3	7.5

ANALYSIS OF MEASURED DROP SIZE DISTRIBUTIONS FOR
EXPERIMENT #19 AT TIME = 4 MINUTES
SIMULATED "MARINE" FOG

DATE = 12JUL78 RUN NUMBER 1 TIME = 8 SLIDE NUMBER 34

ALTITUDE = 0. METERS

TEMPERATURE = 20.0C PRESSURE = 1000.0MB AIR VELOCITY = 29.0M/SEC SLIDE WIDTH = 4.5MM

TOTAL NUMBER OF DROPS (MEASURED) = 128.0
TOTAL NUMBER OF DROPS (CORRECTED) = 139.4

MEAN RADIUS IN MICRONS = 8.2 MEAN SQUARE RADIUS IN MICRONS = 8.3 MEAN VOLUME RADIUS IN MICRONS = 8.4
STANDARD DEVIATION IN MICRONS = 1.3 COEFFICIENT OF VARIATION =0.154 SKEWNESS = -0.364 KURTOSIS = 3.819

MEASURED VISIBILITY IN METERS = 95.0

CALCULATED NUMBER OF DROPS PER CC = 94.1 CALCULATED LWC IN GRAMS PER CUBIC METER = 0.237

RADIUS IN MICRONS =	0.5	1.5	2.5	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5
MEASURED NUMBER OF DROPS =	0.0	0.0	0.0	0.0	2.0	4.0	12.0	24.0	53.0	18.0	8.0	2.0
CORRECTED NUMBER OF DROPS =	0.0	0.0	0.0	0.0	2.5	4.7	13.5	26.4	62.6	19.2	8.4	2.1
NUMBER OF DROPS PER CC =	0.0	0.0	0.0	0.0	1.7	3.2	9.1	17.8	42.3	13.0	5.7	1.4
LWC(GRAMS/CUBIC METER) =	0.0	0.0	0.0	0.0	0.001	0.002	0.010	0.031	0.109	0.047	0.028	0.009
PERCENTAGE OF DROPS =	0.0	0.0	0.0	0.0	1.8	3.4	9.7	18.9	44.9	13.8	6.1	1.5
PERCENTAGE OF LWC =	0.0	0.0	0.0	0.0	0.3	0.9	4.4	13.3	45.9	19.7	11.7	3.8

ANALYSIS OF MEASURED DROP SIZE DISTRIBUTIONS FOR
EXPERIMENT #19 AT TIME = 8 MINUTES
SIMULATED "MARINE" FOG

DATE = 12JUL78 RUN NUMBER 1 TIME = 12 SLIDE NUMBER 32

ALTITUDE = 0. METERS

TEMPERATURE = 20.0C PRESSURE = 1000.0MB AIR VELOCITY = 29.0M/SEC SLIDE WIDTH = 4.0MM

TOTAL NUMBER OF DROPS (MEASURED) = 100.0
TOTAL NUMBER OF DROPS (CORRECTED) = 106.6

MEAN RADIUS IN MICRONS = 9.5 MEAN SQUARE RADIUS IN MICRONS = 9.7 MEAN VOLUME RADIUS IN MICRONS = 9.8
STANDARD DEVIATION IN MICRONS = 1.8 COEFFICIENT OF VARIATION =0.189 SKEWNESS = -0.810 KURTOSIS = 4.606

MEASURED VISIBILITY IN METERS = 130.0

CALCULATED NUMBER OF DROPS PER CC = 51.1 CALCULATED LWC IN GRAMS PER CUBIC METER = 0.203

RADIUS IN MICRONS =	0.5	1.5	2.5	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5	13.5
MEASURED NUMBER OF DROPS =	0.0	0.0	0.0	2.0	0.0	1.0	3.0	9.0	19.0	22.0	27.0	10.0	6.0	1.0
CORRECTED NUMBER OF DROPS =	0.0	0.0	0.0	2.7	0.0	1.2	3.3	9.8	20.4	23.3	28.3	10.4	6.2	1.0
NUMBER OF DROPS PER CC =	0.0	0.0	0.0	1.3	0.0	0.6	1.6	4.7	9.8	11.2	13.6	5.0	3.0	0.5
LWC(GRAMS/CUBIC METER) =	0.0	0.0	0.0	0.000	0.0	0.000	0.002	0.008	0.025	0.040	0.066	0.032	0.024	0.005
PERCENTAGE OF DROPS =	0.0	0.0	0.0	2.5	0.0	1.1	3.1	9.2	19.1	21.9	26.6	9.8	5.8	1.0
PERCENTAGE OF LWC =	0.0	0.0	0.0	0.1	0.0	0.2	0.9	4.1	12.4	19.7	32.4	15.7	12.0	2.5

ANALYSIS OF MEASURED DROP SIZE DISTRIBUTIONS FOR
EXPERIMENT #19 AT TIME = 12 MINUTES
SIMULATED "MARINE" FOG

DATE = 12JUL78 RUN NUMBER 1 TIME = 16 SLIDE NUMBER 30

ALTITUDE = 0. METERS

TEMPERATURE = 20.0C PRESSURE = 1000.0MB AIR VELOCITY = 29.0M/SEC SLIDE WIDTH = 3.6MM

TOTAL NUMBER OF DROPS (MEASURED) = 139.0
TOTAL NUMBER OF DROPS (CORRECTED) = 148.2

MEAN RADIUS IN MICRONS = 9.9 MEAN SQUARE RADIUS IN MICRONS = 10.2 MEAN VOLUME RADIUS IN MICRONS = 10.5
STANDARD DEVIATION IN MICRONS = 2.6 COEFFICIENT OF VARIATION =0.259 SKEWNESS = -0.991 KURTOSIS = 3.776

MEASURED VISIBILITY IN METERS = 240.0

CALCULATED NUMBER OF DROPS PER CC = 24.8 CALCULATED LWC IN GRAMS PER CUBIC METER = 0.119

RADIUS IN MICRONS =	0.5	1.5	2.5	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5	13.5	14.5
MEASURED NUMBER OF DROPS =	0.0	0.0	3.0	1.0	2.0	4.0	7.0	8.0	15.0	15.0	22.0	37.0	20.0	3.0	1.0
CORRECTED NUMBER OF DROPS =	0.0	0.0	4.6	1.3	2.4	4.5	7.7	8.6	16.0	15.8	23.0	38.4	20.7	3.1	1.0
NUMBER OF DROPS PER CC =	0.0	0.0	0.8	0.2	0.4	0.8	1.3	1.4	2.7	2.6	3.8	6.4	3.5	0.5	0.2
LWC(GRAMS/CUBIC METER) =	0.0	0.0	0.000	0.000	0.000	0.001	0.001	0.003	0.007	0.010	0.019	0.041	0.028	0.005	0.002
PERCENTAGE OF DROPS =	0.0	0.0	3.1	0.9	1.6	3.1	5.2	5.8	10.8	10.7	15.5	25.9	14.0	2.1	0.7
PERCENTAGE OF LWC =	0.0	0.0	0.0	0.0	0.1	0.4	1.2	2.1	5.8	8.0	15.6	34.3	23.7	4.5	1.8

RADIUS IN MICRONS =	15.5
MEASURED NUMBER OF DROPS =	1.0
CORRECTED NUMBER OF DROPS =	1.0
NUMBER OF DROPS PER CC =	0.2
LWC(GRAMS/CUBIC METER) =	0.003
PERCENTAGE OF DROPS =	0.7
PERCENTAGE OF LWC =	2.2

ANALYSIS OF MEASURED DROP SIZE DISTRIBUTIONS FOR
EXPERIMENT #19 AT TIME = 16 MINUTES
SIMULATED "MARINE" FOG